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ABSTRACT

This is the second of three sequential course manuals for instructors in X-Ray science and engineering developed at Oregon State University. It consists of outlines for fourteen lectures and eight laboratory exercises with problems and two examinations. Also included is a list of references, equipment, and materials. The purposes, teaching aids, materials, time recommendations, and reference materials are given for each lecture and laboratory exercise. Some of the topics addressed are interaction of X-Rays with matter, gas ionization instrumentation, X-Ray beam factors, X-Ray shielding, and energy dependence of X-Ray measuring instruments. (BB)

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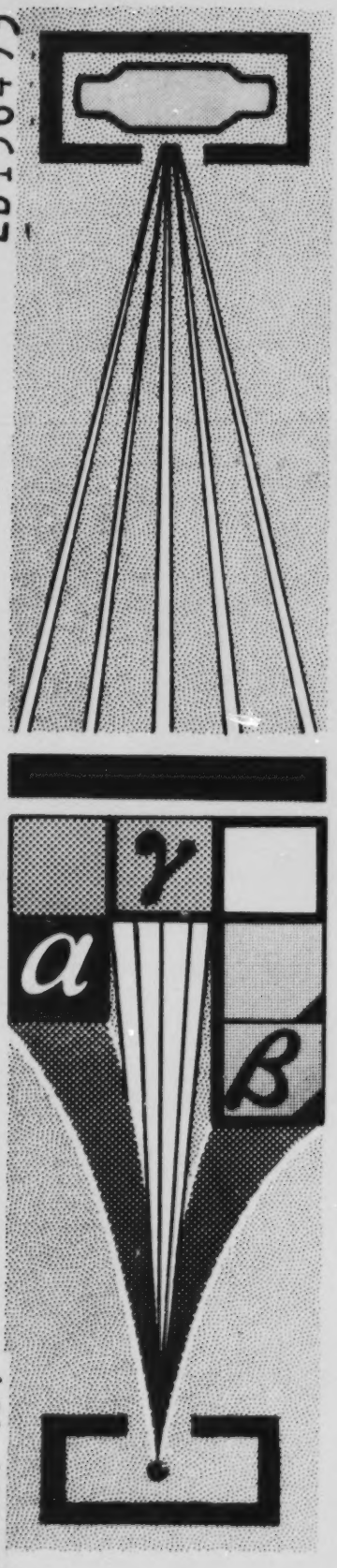

COURSE MANUAL for X-RAY MEASUREMENTS

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
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SE 024 454

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HEW Publication (FDA) 77-8036

COURSE MANUAL

for

X-RAY MEASUREMENTS

(GS-462)

Prepared by:

The X-Ray Science and Engineering Laboratory
Oregon State University

Project Director:
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X-Ray Science and Engineering Laboratory

•

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Deputy Director
Bureau of Radiological Health

This work was carried out under PHS Contract Number 223-72-6314.

BRH
bureau of radiological health

WHO Collaborating Center for
Training and General Tasks in
Radiation Medicine

(This publication supersedes HEW Publication (FDA) 73-8027, January 1973)

July 1977

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Food and Drug Administration
Bureau of Radiological Health
Rockville, Maryland 20857

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FOREWORD

The Bureau of Radiological Health conducts a national program to limit man's exposure to ionizing and nonionizing radiations. To this end, the Bureau (1) develops criteria and recommends standards for safe limits of radiation exposure, (2) develops methods and techniques for controlling radiation exposure, (3) plans and conducts research to determine health effects of radiation exposure, (4) provides technical assistance to agencies responsible for radiological health control programs, and (5) conducts an electronic product radiation control program to protect the public health and safety.

The Bureau publishes its findings in appropriate scientific journals and technical report and note series prepared by Bureau divisions and offices. Under a memorandum of agreement between the World Health Organization and the Department of Health, Education, and Welfare, three WHO Collaborating Centers have been established within the Bureau of Radiological Health, FDA:

WHO Collaborating Center for Standardization of Protection Against Nonionizing Radiations (Office of the Bureau Director)

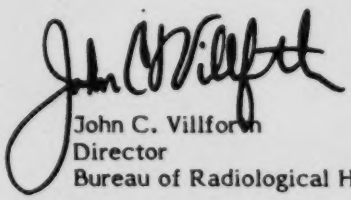
WHO Collaborating Center for Training and General Tasks in Radiation Medicine (Division of Training and Medical Applications)

WHO Collaborating Center for Nuclear Medicine (Division of Radioactive Materials and Nuclear Medicine)

As a WHO Collaborating Center, the Bureau makes available its technical reports and notes to participating WHO members.

Bureau publications provide an effective mechanism for disseminating results of intramural and contractor projects. The publications are distributed to State and local radiological health personnel, Bureau technical staff, Bureau advisory committee members, information services, industry, hospitals, laboratories, schools, the press, and other concerned individuals. These publications are for sale by the Government Printing Office and/or the National Technical Information Service.

Readers are encouraged to report errors or omissions to the Bureau. Your comments or requests for further information are also solicited.



John C. Villforth
Director
Bureau of Radiological Health

PREFACE

Within the Bureau of Radiological Health, the Division of Training and Medical Applications is responsible for programs to reduce unnecessary radiation exposure to the public by improving the practices of those who use radiation in the healing arts. An important aspect of this work is the development and distribution of educational materials, both for students in the health care professions and for the continuing education of individuals who are already in practice.

In 1965, the X-Ray Science and Engineering Laboratory of Oregon State University, under a contract with the Bureau of Radiological Health, initiated a three-course sequence in X-Ray Science. These courses were designed for students who have had no x-ray experience but have had at least 1 year's work in college level physics and mathematics. The manuals developed for use in these courses were made available in 1973 by the Bureau through the Superintendent of Documents, U.S. Government Printing Office. This new set of manuals has been prepared to reflect new technology, new reference material, and the experience gained in teaching. They are also being made available by the Bureau through the U.S. Government Printing Office.

There are three course manuals in this set, one for each course in the sequence. The courses are:

461 Machine Sources of X Ray
462 X-Ray Measurements
463 X-Ray Applications

These manuals are intended for the instructor's use in planning and presenting the courses. Each manual contains lecture outlines and laboratory exercises. An attempt has been made to present the subject matter in as uncomplicated a form as possible. In doing so, some concepts may have been oversimplified but the instructor can increase the degree of sophistication to the limit of student understanding.

The project was directed by the late Dr. E. Dale Trout, Professor of Radiological Physics, and an internationally recognized expert in the fundamentals and use of x radiation. Dr. Trout was assisted by John P. Kelly, Associate Professor, Department of General Science. We welcome comments on your experience with this manual.

James S. Benson

James S. Benson, Project Officer
Deputy Director
Bureau of Radiological Health

CONTENTS

	Page
FOREWORD	iii
PREFACE	iv
INTRODUCTION	vii
ABSTRACT	ix
IN MEMORIAM	x
SECTION I - LECTURES	1
1. INTERACTION OF X RAYS WITH MATTER	3
2. ATTENUATION OF X RAYS	9
Problem Set No. 1	14
3. RADIATION QUANTITIES AND UNITS	17
4. X-RAY DETECTION	21
5. GAS IONIZATION INSTRUMENTATION	25
6. ENERGY DEPENDENCE OF IONIZATION CHAMBER INSTRUMENTS	33
7. SURVEY METER TIME RESPONSE	39
8. X-RAY BEAM FACTORS	43
9. PERSONNEL MONITORING DEVICES	53
10. CHEMICAL DOSIMETRY	61
11. THERMOLUMINESCENT DOSIMETERS	65
12. CORRELATION OF EXPOSURE AND ABSORBED DOSE	71
13. X-RAY SHIELDING	77
Shielding Design Problem Set	82
14. RADIATION PROTECTION SURVEY	87
SECTION II - LABORATORY EXERCISES	91
1. X-RAY OUTPUT WAVEFORM	93
2. FACTORS AFFECTING PATIENT AND OPERATOR EXPOSURE	101
3. DETERMINATION OF X-RAY FIELD DISTRIBUTION	115

CONTENTS (continued)

Page

4. DETERMINATION OF HALF-VALUE LAYER. 121

5. ENERGY DEPENDENCE OF X-RAY MEASURING INSTRUMENTS 137

6. RESPONSE TIME OF SURVEY INSTRUMENTS. 145

7. MEASUREMENT OF X-RAY EXPOSURE WITH PERSONAL MONITORING FILM. . . . 169

8. X-RAY PROTECTION SURVEY. 175

SECTION III - EXAMINATIONS 177

TEST NO. 1 179

FINAL EXAMINATION. 184

APPENDICES 191

A. - EQUIPMENT LIST. 192

B. - BIBLIOGRAPHY 196

INTRODUCTION

In 1965, the X-Ray Science and Engineering Laboratory of Oregon State University, under a contract with the Bureau of Radiological Health, Food and Drug Administration, Department of Health, Education and Welfare, initiated a three-course sequence in X-Ray Science. The Course Manuals developed for use in this course were made available in 1973 by the Bureau of Radiological Health through the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

The Course Manuals as used at Oregon State University are updated each year to reflect new technology, new reference material, and the experience gained in teaching. At the end of the 1974-1975 academic year it was thought advisable to prepare a new set of Manuals as used during that year.

There are three Course Manuals in this set. They are used in a three-course sequence offered in the Department of General Science at Oregon State University.

The courses are:

GS-461 Machine Sources of X Ray - Fall Term
GS-462 X-Ray Measurements - Winter Term
GS-463 X-Ray Applications - Spring Term

The courses must be taken in sequence. Each is a 3-hour credit course and consists of two 1-hour lectures and one 3-hour lab each week. These courses are open to both undergraduate and graduate students. The manuals are intended for the instructor's use in planning and presenting the courses. It is assumed that students will have had no x-ray experience but that they will have at least 1 year's work in college level physics and mathematics.

An attempt has been made to present the subject matter in as uncomplicated form as possible. In so doing some concepts may have been oversimplified, but the instructor can easily increase the degree of sophistication to the limit of student understanding.

An attempt has been made to make each lecture and each laboratory exercise a self-contained entity. This has been done to permit selection of material that could be used to fit the available time, the use of available equipment and the objective of the instructional program.

The equipment has been identified by model and by manufacturer to enable the instructor to substitute equivalent equipment or to alter the course content to make use of available equipment. This method of identification does not constitute a recommendation of a particular piece of equipment by either Oregon State University or the Bureau of Radiological Health, Food and Drug Administration, United States Department of Health, Education and Welfare.

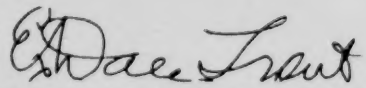
The objective has been to present certain basic material in a manner that will permit great flexibility in the manner in which it is used. We have for 10 years used the manuals for a three-course sequence of classes that have included students from programs in 30 academic disciplines. About 75 percent of the students are premed or predent. Since our courses include things basic to

radiation usage and good practice, students have come from programs in veterinary medicine, physics, geology, electrical engineering, radiation biology, oceanography, fisheries and wildlife, production engineering, nuclear engineering, chemistry, and pharmacy; to name some of them.

Selected sections have been used for a one-term course in Continuing Education and some sections have been presented as 2-day, working, topical seminars.

It is our belief that full appreciation and understanding of the subjects presented require laboratory experience. The lecture material alone could be presented as review material or as indoctrination material to a group where x rays might be of peripheral interest.

One of the more frustrating things encountered in the preparation of a teaching outline such as this is the ever-changing situation so far as references are concerned. New books and technical papers may make any list of references obsolete before such a document appears in print. The instructor must add books and references as they become available. The references cited should always reflect the experience, interests and objectives of the instructor, the institution, and the student.



E. Dale Trout, Project Director
X-Ray Sience and Engineering Laboratory
Oregon State University

April 14, 1976

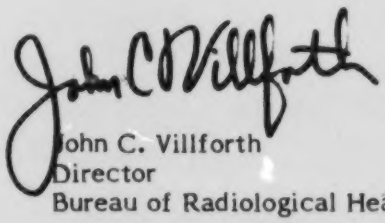
ABSTRACT

Course Manual for X-Ray Measurements (GS-462) is an instructor's guide consisting of an outline of lectures and laboratory exercises with problems and examinations. Included is a list of references, equipment and materials.

The designation GS-462 is the course number at Oregon State University and it is carried thoughout the text. The course is offered by the Department of General Science.

IN MEMORIAM

With Dr. Trout's death in February 1977, the Bureau of Radiological Health lost a valued colleague. Dr. Trout contributed his unique expertise to the Bureau's advisory committees, and to the development of both our diagnostic x-ray performance standard and training programs in the area of medical radiation. Many of the Bureau's senior staff members received their original training in radiological health from Dr. Trout at Oregon State University. Over a period of many years, he served us well as a counselor, a teacher, and a friend. We will miss him.



John C. Villforth
Director
Bureau of Radiological Health

August 4, 1977

SECTION I. LECTURES

GS-462. X-RAY MEASUREMENTS

LECTURE NO. 1

TITLE:	Interaction of X Rays with Matter
PURPOSE:	To study the fundamental interactions of x rays with matter
TIME:	1 hour
VISUAL AIDS:	Blackboard Slide projector for slides illustrating basic photon interactions
HANDOUTS:	None
REFERENCES:	Attix, Roesch and Tochilin Radiation Dosimetry Johns and Cunningham The Physics of Radiology Radiological Health Handbook Ter-Pogossian Physical Aspects of Diagnostic Radiology

1. INTERACTION OF X RAYS WITH MATTER

I. INTRODUCTION

A knowledge of the basic interactions of x rays with matter is essential to the understanding of the principles of x-ray detection and measurement.

II. DEFINITIONS OF INTERACTIONS

A. When x rays interact with matter they may lose energy and/or change their direction of travel

1. Loss of energy is referred to as absorption
2. Change in direction of travel is called scattering

a. Elastic scattering - no loss in energy
b. Inelastic scattering - loss in energy

B. Ionization

1. Ions are free electrons or atoms carrying an electric charge
2. Ionization is the process by which ions are formed

a. Generally result of removal of electron(s)
b. Ion pair - positive and negative ion

(1) Negative ion - electron
(2) Positive ion - remaining atom

III. MECHANISMS OF INTERACTIONS

A. Photoelectric effect

1. An x-ray photon imparts all of its energy to a bound inner orbital electron of an atom. All or nothing energy transfer.

2. An electron is ejected and an ion pair is formed

a. $(KE)_{e^-} = h\nu - w$
b. $h\nu$ = initial photon energy
c. w = atomic binding energy

3. The electron is called a photoelectron

a. It has sufficient energy, in general, to produce many hundreds of additional ion pairs as it travels through matter expending its energy

4. Let τ = fraction of x-ray photons removed from beam by photoelectric effect per unit thickness of absorbing material (fig. 462-1)

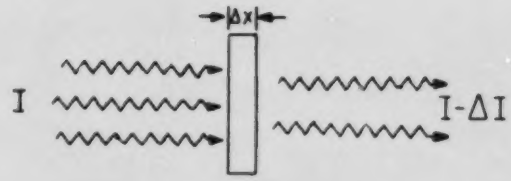


Figure 462-1. Photon attenuation.

a. I = number of incident photons. ΔI = number of photons removed by photoelectric effect in absorber of thickness ΔX

b. $\tau = -\frac{\Delta I}{I} / \Delta X \propto \frac{Z^4}{E^3}$

5. Photoelectric effect predominates at low energies and high Z materials

   a. For tissue the photoelectric effect becomes negligible above 200 keV

B. Compton effect

1. If a photon is incident upon a "free" or loosely bound electron it may impart part of its energy to the electron and be scattered
2. The electron receiving energy is called a Compton electron
3. The results of ionization are identical to those of the photoelectric effect
4. The remaining photon energy appears as a lower energy photon traveling in a direction with an angle θ to the initial photon's direction of travel
5. The energy of the scattered photon is a function of the initial photon energy and the angle of scatter (fig. 462-2)

Figure 462-2. Compton scattering.

$$h\nu_1 = \frac{h\nu_0}{1 + \frac{h\nu_0}{m_0 c^2}(1 - \cos\ \theta)}$$

6. Let σ = fraction of x-ray photons removed from the beam by the Compton effect per unit thickness of absorber

   a. $\sigma \propto \frac{Z}{E}$

b. The Compton effect predominates at intermediate energies, that is, 600 keV-2.5 MeV

C. Pair production

1. An x-ray photon interacts with the electric field of the nucleus giving up all its energy to the creation of a pair of "electrons"

   a. One electron is negatively charged (e^-)
   b. One positron is positively charged (e^+)

2. The energy threshold for pair production is 1.02 MeV. Photon energy in excess of 1.02 MeV is shared as the kinetic energy of the "electron" pair

3. Both the electron and positron interact with matter to produce ion pairs. This is the same process as Compton or photoelectric electrons.

4. The positron combines with an electron in annihilation producing two back-to-back 0.51 MeV photons (fig. 462-3)

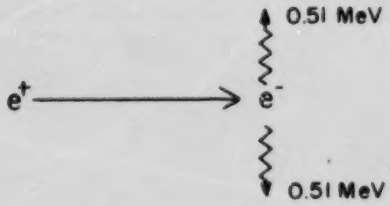


Figure 462.3. Annihilation process.

5. Let k = fraction of x-ray photons removed from the beam by pair production per unit thickness of absorber

   a. $K \propto Z^2 \ln E$ where $E > 1.02$ MeV
   b. Pair production predominates at high E and high Z

D. Linear attenuation coefficient (fig. 462-4)

1. $\mu = \tau + \sigma + k = \frac{-\Delta I}{I} \Big/ \Delta X$

2. $I = I_o e^{-\mu x}$ or $\frac{I}{I_o} = e^{-\mu x}$

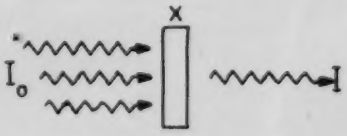


Figure 462-4. Linear attenuation coefficient.

3. Unit, cm^{-1}

IV. DIAGRAMS OF INTERACTION

A. Photoelectric effect (fig. 462-5)

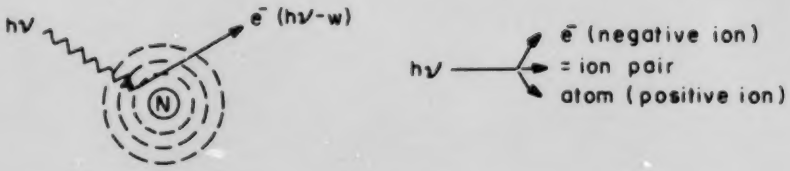


Figure 462-5. Photoelectric effect.

B. Compton effect (fig. 462-6)

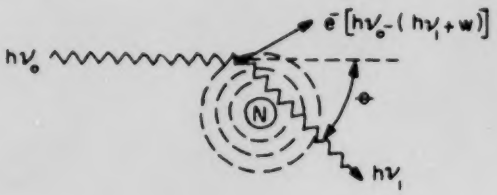


Figure 462-6. Compton effect.

C. Pair production (fig. 462-7)

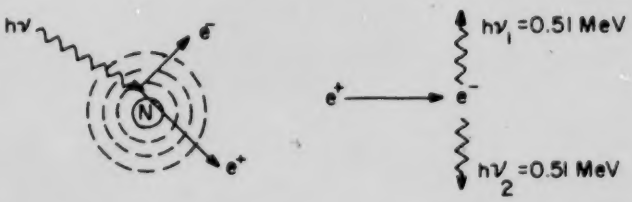


Figure 462-7. Pair production.

LECTURE NO. 2

TITLE: Attenuation of X Rays

PURPOSE: To study the attenuation and absorption of x rays by matter

TIME: 2 hours

VISUAL AIDS: Blackboard

HANDOUTS: None

REFERENCES: Attix, Roesch and Tochilin
Radiation Dosimetry

ICRU Report 19

Johns and Cunningham
The Physics of Radiology

Whyte
Principles of Radiation Dosimetry

2. ATTENUATION OF X RAYS

I. INTRODUCTION

The three principal kinds of x- and γ-ray interactions with matter are the photoelectric effect, Compton effect, and pair production. In these interactions the photon tends to lose much or all of its energy in a single interaction. In our study we are concerned with the combined effect of all interactions. (Interactions refer to processes whereby the energy or direction of the x-ray photon is altered.) The beam attenuating effect of these interactions may be described by various attenuation coefficients.

II. ABSORPTION AND ATTENUATION COEFFICIENTS

A. Linear attenuation coefficient - μ

1. Defined as the fractional change in intensity per unit thickness because of interactions in a given material

   a. $\mu = \Delta N / N \Delta X$
   b. ΔN = number of photons actually <u>removed</u> from beam in thickness ΔX

2. It is a function of density and atomic number

B. Mass attenuation coefficient - μ/ρ

1. Defined as the fractional decrease in intensity per unit mass because of interactions in a given material

   a. $\mu/\rho = \Delta N / N \Delta X \rho = \mu_m$
   b. ρ = density of the materials

2. For x or γ radiation

$$\mu/\rho = \tau/\rho + \frac{\sigma}{\rho} + \frac{\sigma \text{ coh}}{\rho} + \frac{k}{\rho} = \mu_m \quad cm^2 g$$

III. BEHAVIOR OF μ/ρ or μ_m

A. In low Z materials such as, oxygen:

1. μ_m falls rapidly in the 10 - 100 keV region
2. μ_m slowly decreases in the 100 keV - 2 MeV region Compton is the predominate interaction
3. μ_m increases in the region above 50 MeV

B. In medium Z materials such as, copper:

1. μ_m falls until both the photoelectric and Compton effects are equal, which occurs at about 125 keV

2. μ_m slowly decreases until both Compton and pair production effects are equal, which occurs at about 9 MeV. Compton predominates in the 500 keV - 3 MeV region

3. μ_m increases in the region above 8 MeV

C. In high Z materials such as lead:

1. μ_m follows the same trend but there is no region where the Compton effect alone is important
2. The photoelectric effect = Compton effect at about 500 keV
3. The total effect is about 75 percent Compton at 1 - 2 MeV
4. The minimum μ_m occurs at about 3 MeV
5. The Compton effect = pair production at about 4.5 MeV

IV. ATTENUATION OF X RAYS

A. Assume narrow beam geometry and a monoenergetic beam of x rays (fig. 462-8)

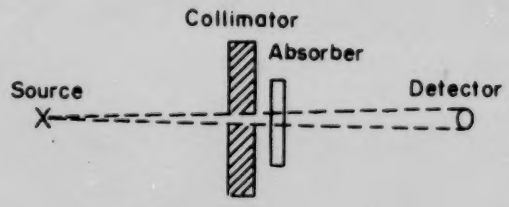


Figure 462-8. Narrow beam geometry.

B. It can be shown that $I = I_0 e^{-\mu x}$ where:

1. I_0 = initial beam intensity at the detector
2. I = beam intensity at the detector after passing through a thickness of absorber
3. x = thickness of absorber
4. μ = linear attenuation coefficient of the material for indirectly ionizing particles

C. Half-value layer

1. Defined as the thickness of a specified absorber (material) required to reduce the x-ray beam intensity by a factor of 1/2 (fig. 462-9)

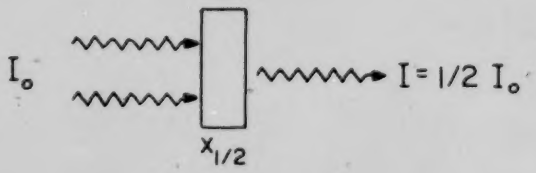


Figure 462-9. Half-value layer.

2. For a monoenergetic x-ray beam:

a. $I = I_0 e^{-\mu x}$

b. If $x = x_{\frac{1}{2}}$ (the half-value layer) then:

$I/I_0 = e^{-\mu x_{\frac{1}{2}}} = \frac{1}{2}$

c. $\therefore e^{-\mu x_{\frac{1}{2}}} = 2$ and $\mu x_{\frac{1}{2}} = \ln 2 = 0.693$

d. HVL (the half-value layer) = $x_{\frac{1}{2}} = 0.693/\mu$

3. Example: calculate the HVL in Al for 0.1 MeV (100 keV) photons

a. $\mu/\rho = 0.167$ cm^2/g

b. ρ(Al) = 2.7 g/cm^3

c. $\mu = (\mu/\rho)\rho = (0.167)(2.7) = 0.45$ cm^{-1}

d. HVL = 0.693/0.45 = 1.54 cm Al = 15.4 mm Al

D. Build-up factor

1. Defined to account for the scatter contribution under broad beam conditions (fig. 462-10)

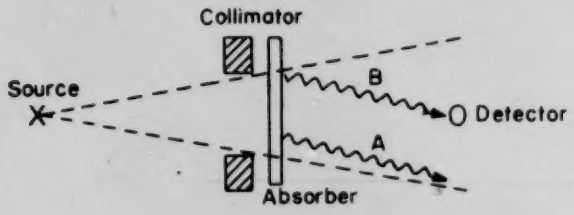


Figure 462-10. Broad beam geometry.

2. Build-up factor B = $\frac{\text{observed broad beam intensity}}{\text{narrow beam intensity}}$

3. $B = I/(I_0 \exp(\mu/\rho)\rho x)$

4. $\therefore I = I_0 B e^{-(\mu/\rho)\rho x}$

5. B depends upon:

a. Geometry
b. Absorber material
c. Absorber thickness
d. Primary photon energy

E. Backscatter

1. When a photon beam strikes the surface of an absorber, the intensity in front of the absorber is greater than that without the absorber (fig. 462-11)

2. Intensity $I_1 > I_0$ because of scattering of radiation from the absorber back to the detector

3. Backscatter depends upon the:

a. Incident photon beam energy
b. Beam area (size)
c. Atomic number of absorber

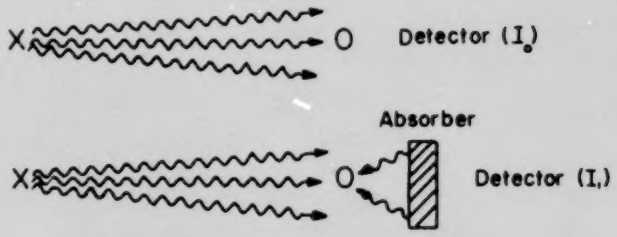


Figure 462-11. Backscatter.

4. Backscatter varies from a negligible value to more than 50 percent of the incident exposure under certain conditions.

GS-462. PROBLEM SET NO. 1

1. Calculate the fractional decrease in beam intensity when a beam of 50-keV x rays passes through a 1.00 cm aluminum absorber.

2. Compute the HVL for 100 keV x rays in aluminum and copper.

3. The exposure rate of 50 keV x rays incident upon an aluminum absorber is 1 R/hr. If the transmitted exposure rate is 1 mR/hr, what is the thickness of the absorber?

4. Find the photon energy of a beam of monoenergetic x rays if the HVL is 0.61 cm lead.

GS-462. PROBLEM SET NO. 1
KEY

1. Calculate the fractional decrease in beam intensity when a beam of 50 keV x rays passes through a 1.00 cm aluminum absorber.

   Ans: For 50 keV photons, μ/ρ (Al) $= 0.36\ cm^2/g$
   and $\rho = 2.7\ g/cm^3$

   $I = I_o e^{-\mu x}$ so $\frac{I}{I_o} = e^{-\mu x}$ $= e^{-(0.36)\ (2.7)(1.00)}$
   $= e^{-0.973} = 0.375$

   Fractional decrease: $1 - 0.375 = 0.625$

2. Compute the HVL for 100 keV x rays in aluminum and copper.

   Ans: $HVL = \frac{0.693}{\mu} = \frac{0.693}{(\mu/\rho)(\rho)}$

   For Al at 100 keV $\mu/\rho = 0.17\ cm^2/g$ and $\rho = 2.7\ g/cm^3$

   For Cu at 100 keV $\mu/\rho = 0.47\ cm^2/g$ and $\rho = 8.96\ g/cm^3$

   $HVL_{Al} = \frac{0.693}{(0.17)\ (2.7)} = 1.51$ cm

   $HVL_{Cu} = \frac{0.693}{(0.47)\ (8.96)} = 0.164$ cm

3. The exposure rate of 50 keV x rays incident upon an aluminum absorber is 1 R/hr. If the transmitted exposure rate is 1 mR/hr, what is the thickness of the absorber?

   Ans: $I = I_o e^{-\mu x}$. At 50 keV $\mu = (\mu/\rho)\ (\rho) = (0.36)\ (2.7) = 0.972$

   $\frac{I}{I} = \frac{1.0}{1000} = e^{-\mu x} = 0.001$

   $e^{-6.91} = 0.001$ so $x = \frac{6.91}{\mu} = \frac{6.91}{0.972} = 7.12$ cm

4. Find the photon energy of a beam of monoenergetic x rays if the HVL is 0.61 cm lead.

   Ans: $HVL = \frac{0.693}{\mu} = \frac{0.693}{(\mu/\rho)\ (\rho)}$

   For lead $\rho = 11.4$ g/cm

   $\mu/\rho = \frac{0.693}{(0.61)\ (11.4)} = \frac{0.693}{6.95} = 0.0997\ cm^2/g$

   so keV for μ/ρ of 0.1 for lead $\approx$ 700 keV

LECTURE NO. 3

TITLE:	Radiation Quantities and Units
PURPOSE:	To present the quantities and units used in the study of x-ray measurements
TIME:	1 hour
VISUAL AIDS:	Blackboard
HANDOUTS:	None
REFERENCES:	ICRU Report 19

3. RADIATION QUANTITIES AND UNITS

I. INTRODUCTION

In order to understand the techniques used in x-ray measurements one must be familiar with the terminology used. This requires that we define certain radiation quantities and units.

II. SPECIAL UNITS

A. Roentgen for exposure (R)

1. 1 R = 2.58×10^{-4} coulomb/kg air
2. 1 R = 1 esu/0.001293 g air
3. 1 R = 1 esu/cm^3 dry air at STP
4. With present techniques it is difficult to measure exposure for photon energies below a few keV and above a few MeV

B. Rad for absorbed dose

1. 1 rad = 0.01 joule/kg material
2. 1 rad = 100 ergs/g material
3. When rad may be confused with the symbol for radian, rd may be used as the symbol for rad

III. DEFINITIONS OF RADIATION QUANTITIES

A. Directly ionizing particles

1. Charged particles with sufficient kinetic energy to produce ionization by collision
2. Examples: electrons, protons, α particles

B. Indirectly ionizing particles

1. Uncharged particles which can liberate directly ionizing particles or can initiate a nuclear transformation
2. Examples: photons, neutrons

C. Ionizing radiation

1. Any radiation consisting of directly or indirectly ionizing particles or a mixture of both

D. Energy imparted

1. Difference between the sum of the energies of all ionizing particles which have entered the volume and the sum of the energies of all those which have left the volume. Excludes the energy equivalent of any increase in rest mass that took place in nuclear or elementary particle reactions.

2. The term mean energy imparted to matter is identical to the quantity called integral absorbed dose

3. Energy imparted cannot always be equated to heat produced because of possible changes in interatomic bond energies

E. Exposure (X)

1. Special unit - roentgen

2. $X = \frac{dQ}{dm}$

dQ = sum of the electrical charges on all ions of one sign produced in air when all the electrons (negatrons and positrons) liberated by photons in a volume element of air whose mass is dm are completely stopped in air

F. Absorbed dose (D)

1. Special unit - rad

2. $D = \frac{d\bar{\epsilon}_D}{dm}$

$d\bar{\epsilon}_D$ = energy imparted by ionizing radiation to the matter in a volume element and dm is the mass of the matter in that volume element

G. Other quantities of interest

1. Particle fluence $\Phi = \frac{dN}{da}$

2. Flux density (particle fluence rate)

3. Energy fluence $\psi = \frac{dE_{fl}}{da}$

4. Intensity, (I), energy flux density, energy fluence rate = $\frac{d\psi}{dt}$

5. Kerma $K = \frac{dE_k}{dm}$

6. Mass attenuation coefficient $\mu/\rho = \tau/\rho + \frac{\sigma}{\rho} + \frac{\sigma \text{ coh}}{\rho} + \frac{k}{\rho}$

7. Mass energy transfer coefficient $\mu_{tr}/\rho = \frac{\tau a}{\rho} + \frac{\sigma a}{\rho} + \frac{K_a}{\rho}$

8. Mass stopping power $S/\rho = \frac{1}{\rho} \frac{dE}{dl}$

9. Mean energy ($\bar{W}$) expended in gas per ion formed ($\bar{W}$) = $\frac{E}{N}$

H. Relative biological effectiveness (RBE)

Factor used in radiobiology to compare biological effectiveness of absorbed doses of different types of ionizing radiations

I. Dose equivalent (H)

1. Used for radiation protection purposes
2. H = (D) (Q) (N)

   a. D = absorbed dose in rads
   b. Q = quality factor, LET dependent factor, that expresses on common scale for ionizing radiations the irradiation incurred by exposed persons
   c. N = other modifying factors

3. Unit of dose equivalent - rem

   a. Equal to dose in rads times appropriate modifying factors
   b. For our purposes we can assume 1 R = 1 rad - 1 rem.

LECTURE NO. 4

TITLE: X-Ray Detection

PURPOSE: To outline the basic principles of x-ray detection

TIME: 1 hour

VISUAL AIDS: Blackboard

HANDOUTS: None

REFERENCES:

Attix, Roesch and Tochilin
Radiation Dosimetry

Johns and Cunningham
The Physics of Radiology

Spiers and Reed
Radiation Dosimetry

Ter-Pogossian
Physical Aspects of Diagnostic Radiology

4. X-RAY DETECTION

I. INTRODUCTION

X-ray detection systems depend, for their operation, on ionization and/or excitation produced in the system by x-ray interactions with the system (matter).

II. MEDIA

A. Gases

1. Usually air enclosed in a chamber having electrically conducting walls and a collecting (center) electrode (fig. 462-12)

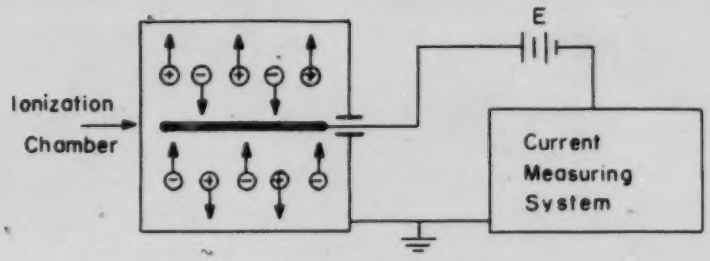


Figure 462-12. Gas ionization system.

2. Ions produced as a result of interactions of the x rays with the gas (air) are collected by the electrostatic field (E) between chamber walls and collecting (center) electrode
3. Ionization current ∝ incident x-ray intensity

B. Photographic emulsions

1. Film emulsion
   Silver bromide (AgBr) suspended in gelatin
2. Ionization within emulsion renders AgBr crystals susceptible to action of developer

   a. Developer reduces Ag^+ to Ag producing darkening of the film
   b. The degree of darkening (density) is measured with a "densitometer"
   c. Film density ∝ quantity of incident x rays

C. Luminescent detectors

1. Scintillation crystals

   a. Excitation of crystals through x-ray interactions
   b. Results in "immediate" de-excitation with the wavelength of energy emitted in the visible light region

c. Sodium iodide is used extensively
d. A photomultiplier tube, photocell, and so forth, are used to detect the emitted light
e. The quantity of light ∝ energy of the incident x rays
f. Fluorescence

(1) Fluorescent screens - Zn CdS
(2) Intensifying screens $CaWO_4$, $BaPbSO_4$, La_2O_2S: Tb, and Gd_2O_2S: Tb

2. Thermoluminescent crystals

a. Excitation is produced through x-ray interactions
b. The excitation energy is stored by the crystal
c. De-excitation is induced by crystal heating
d. De-excitation energy is emitted as light and detected by a photomultiplier tube
e. The light emitted ∝ quantity of incident x rays
f. Commonly used crystals:

(1) LiF
(2) CaF_2
(3) $CaSO_4$

3. Radiophotoluminescent glass

a. The crystal is excited through x-ray interactions
b. Materials fluoresce when exposed to ultraviolet light
c. Fluorescence is measured with a fluorimeter
d. The light intensity ∝ quantity of x-ray interactions
e. One material used is silver activated metaphosphate glass

. Chemical solutions

1. Ionization from x-ray interactions induces a chemical reaction
2. The end products produced ∝ quantity of incident x rays
3. Fricke dosimeter

a. Ferrous sulfate is converted to ferric ions when exposed to x rays
b. $Fe^{++} + h\nu \rightarrow Fe^{+++}$ in dilute sulfuric acid solution
c. Quantity of Fe^{+++} (ferric ions) produced ∝ to the energy absorbed

(1) Determined by absorption spectroscopy or chemical titration
(2) Not a sensitive system

E. Other systems

1. Xerographic plates (Xerox)
2. Electron system (Xonics)

LECTURE NO. 5

TITLE: Gas Ionization Instrumentation

PURPOSE: To study the characteristics of gas ionization instruments

TIME: 2 hours

VISUAL AIDS: Blackboard
Condenser R-meter, GM survey meter, DC amplifier survey meter, vibrating reed survey meter

HANDOUTS: None

REFERENCES:

Attix, Roesch and Tochilin
Radiation Dosimetry

Johns and Cunningham
The Physics of Radiology

Spiers and Reed
Radiation Dosimetry

Ter-Pogossian
Physical Aspects of Diagnostic Radiology

5. GAS IONIZATION INSTRUMENTATION

I. INTRODUCTION

A. Basic x-ray measuring instruments are designed to measure the number of ions formed in a gas through interaction of x rays

B. The number of ions collected in a gas ionization chamber is a function of the electric field strength between the collecting electrodes

C. Diagram of basic system (fig. 462-13)

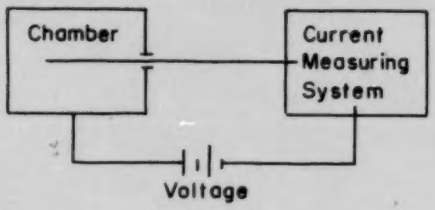


Figure 462-13. Diagram of basic system.

II. CHARGE COLLECTION

There are at least 5 separate response regions, for a given ion chamber, which are dependent upon chamber voltage (fig. 462-14)

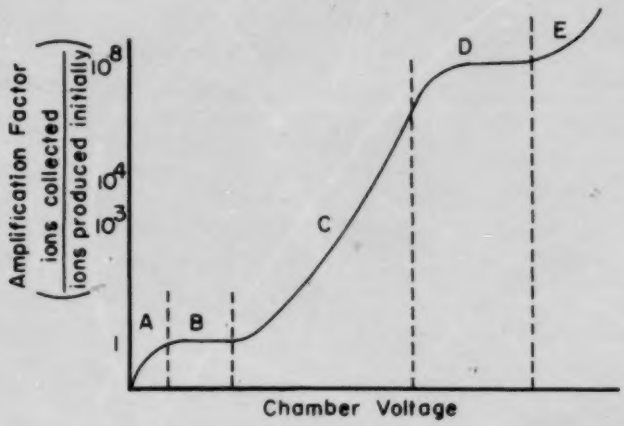


Figure 462-14. Gas amplification versus chamber voltage.

A. Recombination region

1. Low chamber voltage with resulting weak electric field
2. Some ions recombine before they are collected
3. Recombination decreases as the chamber voltage increases

B. Ionization chamber region

1. The voltage is high enough so that there is effectively no recombination

   a. All of the ions produced are collected
   b. The gas amplification is one

2. This region is best suited for the measurement of exposure
3. The region persists over a fairly large voltage range
4. When all ions produced in the ionization chamber are collected, the current flow will be 0.93×10^{-3} A $cm^{-3}/R\ h^{-1}$

C. Proportional chamber region

1. As the voltage is increased above the ionization chamber region, the electric field accelerates the electrons formed to a velocity high enough to produce additional ionization (gas amplification--by collision)

2. For every initial ion pair formed by the radiation, a larger number is received by electrodes

3. The number of ions collected is proportional to the number of ions initially formed

4. Typical amplification is 10^3 - 10^4

5. This requires a very stable voltage supply since the amplification factor changes rapidly with voltage

6. You no longer measure current flow but detect individual ionizing events

7. This region is not basically suited for measuring exposure

8. This region is used extensively for charged particle measurements

Particle	Primary Ions	Ions Collected
α	10^5	10^8
β	10^3	10^6

9. You can differentiate between α and β by the pulse size

D. Geiger-Mueller region

1. Above the proportional region the amplification factor may reach 10^8
2. Even a low energy β or x ray can initiate sufficient ion formation to cause complete discharge of the chamber
3. You count individual events
4. This region is not suited for the measurement of exposure

E. Continuous discharge region

1. Voltages above GM result in continuous discharge (arcing)

III. ION RECOMBINATION

A. In the ionization chamber region some ion recombination can and does occur. The two basic processes of recombination are:

1. Initial recombination

a. These are ions that recombine in close proximity to their point of formation
b. Some initial recombination will occur regardless of chamber voltage

2. General recombination

a. This is random recombination which occurs at other than points of ion formation
b. General recombination can be calculated. It is a function of:

(1) Chamber shape (spherical, cylindrical, parallel plate)
(2) Electrode spacing
(3) Gas (usually air)
(4) Chamber voltage
(5) Exposure rate
(6) Chamber construction

3. The ratio of ions collected to ions formed is termed collection efficiency F

a. You strive for 0.99+ efficiency
b. This determines intensity limit for ion charge collecting systems

IV. EXPOSURE RATE IONIZATION CHAMBER INSTRUMENTS

A. DC amplifier type (fig. 462-15)

1. This includes direct coupled systems such as the Victoreen model 510 Roentgen Ratemeter, model 740 "Cutie Pie" survey meter

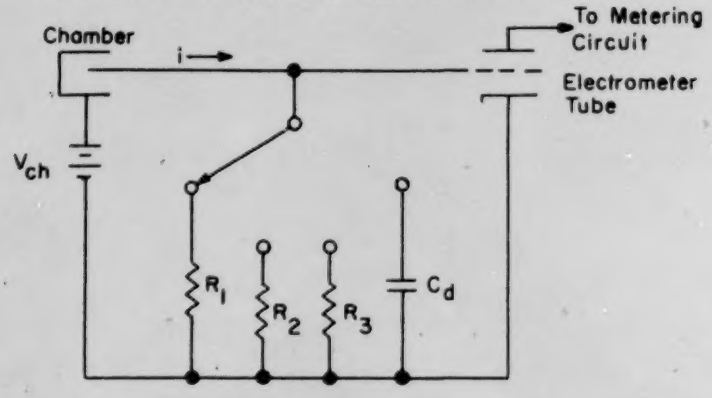


Figure 462-15. DC amplifier.

2. The electrometer tube is usually a triode, small in size, with very high grid leakage resistance
3. The major problem in DC amplifiers is drift. A change in system voltages will produce a signal which is indistinguishable from the ion current.
4. Example: Victoreen 740

   a. Chamber volume = 586 cm^3, full-scale on X 1 range, 25 mR/h
   b. R 1 = 4×10^{11} ohms, scale range X 1
   c. R2 = 4×10^{10} ohms, scale range X 10
   d. R3 = 4×10^{9}, ohms, scale range X 100
   e. Let exposure rate dx/dt = 25 mR/h and use X 1 range, R = 4×10^{11} ohms, i=dQ/dt = coulombs/sec
   f. 1 Roentgen = 1 esu/cm^3, 1 coulomb = 3×10^9 esu
      i = v dx/dt = (586 cm^3) (25 x 10 $^{-3}$ R/h) (1 esu/cm^3/R) (1 h/3.6 x 10^3 sec) (1 coulomb/3 x 10^9 esu)
      = 0.136×10^{-11} amp
   g. The voltage drop across resistor R 1 (grid voltage on electrometer tube) is:
      v = iR = (0.136×10^{-11}) (4×10^{11}) = 0.544 volts
   h. Assume the above except let dx/dt = 2500 mR/h and R3 = 4×10^9 ohms (X 100 range)
      i = 0.136×10^{-9} amp
      v = (0.136×10^{-9}) (4×10^9) = 0.544 volts

B. AC amplifier types (fig. 462-16)

1. A vibrating reed or vibrating capacitor converts the d.c. signal to a.c. (Victoreen model 440 and 444 survey meters, Victoreen model 555 Radocon)

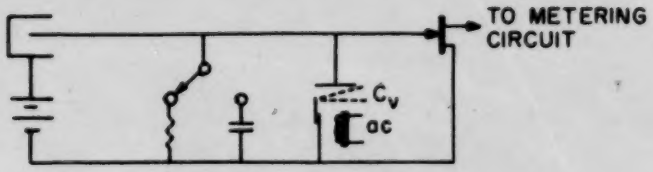


Figure 462-16. Vibrating reed electrometer.

2. The amplified signal is drift-free
3. An a.c. amplifier permits greater sensitivity

V. EXPOSURE (CHARGE COLLECTING/DISSIPATING) SYSTEMS

A. Condenser chamber type (R-meter) (fig. 462-17)

1. A capacitor is charged and then partially discharged because of the ion current flow

   a. Charge ∝ voltage ∝ exposure

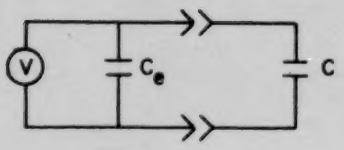


Figure 462-17. R-meter equivalent circuit.

(1) V= electrometer charger-reader
(2) C_e = electrometer capacitance
(3) C = ion chamber capacitance

b. Charge Q = CV so $\Delta Q = C\Delta V \propto R$

(1) Q = vR esu = vR/3 x 10^9 coulombs
(2) $\Delta V/R \propto \Delta V/\Delta Q \propto 1/C$
(3) $\Delta V = vR/3 \times 10^9 \cdot 1/C$
$\Delta V/R$ = sensitivity = S

2. In use, C and C_e charged to V_o

a. When the chamber is exposed to x rays, V_o on C drops to V_1. When C is reconnected to C_e (still charged to V_o) the charge on the two capacitors is shared and the electrometer indicates a "shared" voltage, V_s.

(1) $V_s < V_o$
(2) $V_s > V_1$

b. The measured voltage drop = $V_o - V_s = V_m$
c. The true voltage drop on chamber = $V_o - V_1 = V_t$
d. If Q = charge liberated by the exposure, then:

(1) $V_t = Q/C$
(2) $V_m = Q/C + C_e$
(3) $V_t/V_m = C + C_e/C$

3. In the R-meter, $V_o \approx 525$ volts and V_m (the full-scale voltage) ≈ 275 volts

a. A 25R chamber would have sensitivity, S, of 525 - 275V/25R = 10 V/R
b. The chamber capacitance, C, is typically about 50 pF
c. Knowing V_o, S of the system and C, we can calculate C_e, S of chamber and the effective volume, v, of the chamber

Example:

(1) Assume the 25 R chamber with V_o = 525 volts and S for the electrometer/chamber system = 10 V/R. When the fully charged chamber is connected to the completely discharged electrometer, the scale reading is 10.0 R (discharge check).

(2) A scale reading of 10.0 R corresponds to a voltage drop of (10 V/R) (10 R) = 100 volts and a final voltage of 525 -100

= 425 volts. This loss of charge from the chamber Q = CV = (50 pF) (100 V) charged the electrometer to 425 volts so

$C_e = C\ V_{drop}/V_{read} = (50)\ (100/425) \therefore C_e = 11.8$ pF

(3) $V_t/V_m = C + C_e/C = 50 + 11.8/50 = 1.24$ so
$V_t = 1.24\ V_m = (1.24)\ (100) = 124$ volts, $\therefore$ S of chamber = 12.4 V/R

(4) $V = vR/3 \times 10^9\ C$, $v = V\ (3 \times 10^9\ C)/R$ and $V/R = S$
$v = (12.4)\ (3 \times 10^9)\ (50 \times 10^{-12}) = 1.86\ cm^3$

B. Vacuum tube electrometers (Baldwin-Farmer)

1. Use separate charging and reading systems (fig. 462-18)

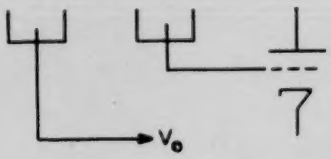


Figure 462-18. Vacuum tube electrometer.

2. Let V_o = charging voltage
X_o = voltage read after charging
$X_o < V_o$ due to charge sharing
$V_{o/X_o} = C = C_{e/C}$

If the chamber is recharged and exposed and we call the resulting reading X_1, then the voltage loss is $X_o - X_1 = V_m$ and $V_t = (X_o - X_1)\ (C + C_{e/C}) = (X_o - X_1)\ V_o/X_o$ and $S = V_{t/R}$

VI. CLASSES OF INSTRUMENTS

A. Survey instruments ($\pm$ 10 - 20 percent)

B. Laboratory Instruments ($\pm$ 1 - 5 percent)

C. Personnel Monitoring Instruments ($\pm$ 5 - 20 percent)

LECTURE NO. 6

TITLE: Energy Dependence of Ionization Chamber Instruments

PURPOSE: To discuss the factors which affect the energy dependence of x-ray measuring instruments

TIME: 1 hour

VISUAL AIDS: Blackboard
Standard Air Chamber

HANDOUTS: None

REFERENCE: Attix, Roesch and Tochilin
Radiation Dosimetry

Snell
Nuclear Instruments and Their Uses

Spiers and Reed
Radiation Dosimetry

6. ENERGY DEPENDENCE OF IONIZATION CHAMBER INSTRUMENTS

I. ENERGY DEPENDENCE

A. Instrument response per roentgen as a function of photon energy. Response is the ratio of the indicated to true exposure (fig. 462-19).

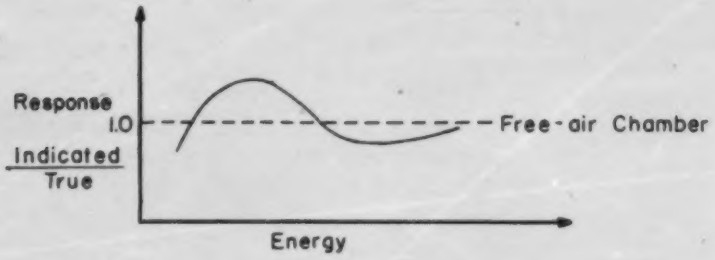


Figure 462-19. Response versus energy.

II. FREE AIR (STANDARD AIR) CHAMBER

A. The primary standard used to measure ionization in air because x- or γ-radiation is the standard air chamber (fig. 462-20)

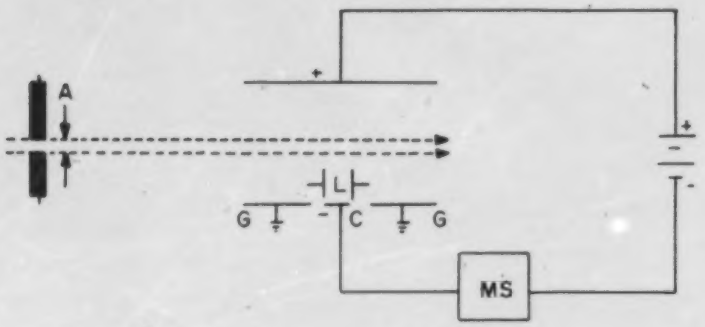


Figure 462-20. Standard air chamber.

B. The x rays interact in air and all ions are collected in air

C. An accurately defined air volume, A x L, is defined

D. All ions produced outside the defined volume by primary electrons originating within the defined volume must be collected

1. Therefore, as photon energy increases, the distance between the defined air volume and the collecting plates must increase so that secondary electrons do not strike the plates and lose ionization potential.

2. The upper limit is about 2 - 3 MeV

   a.

E-keV	Range
100	0.15 m (0.5 ft)
500	1.27 m (4 ft)
1,000	3.05 m (10 ft)
3,000	14 m (45 ft)

   b. High energy chambers are operated at high air pressure

E. Electronic equilibrium must exist in the collecting volume

F. Exposure, P_1, at defined air volume A x L is:

$P_1 = \Delta Q/\rho A_1 L \cdot 1/2.58 \times 10^{-4}$ roentgens where:
ΔQ = charge collected in coulombs
ρ = density of air in kg/cm^3
A_1 = cross sectional area of beam in plane of P at a distance, f_1, from the source, in cm^2
L = length of collecting plate, in cm

1. The exposure, P, at the beam defining diaphragm located at a distance f cm from the source is:

$$P = \left[f_1/f\right]^2 \quad \Delta Q/\rho A_1 L \cdot 1/2.58 \times 10^{-4} \text{ roentgens}$$

2. Since $A = A_1$

$P = Q/AL \cdot 1/2.58 \times 10^{-4}$ roentgens

3. Example: Assume $A = 0.5\ cm^2$, L = 8 cm, Q = 0.112 C in 2 min, $= 1.293 \times 10^{-6}\ Kg/cm^3$ at STP

   a. Mass of air $AL = (1.293 \times 10^{-6})(0.5)(8) = 5.172 \times 10^{-6}$ Kg

   b. $P = 1.12 \times 10^{-7}$ C/5.172×10^{-6} Kg x 1 KgR/2.58×10^{-4} = 84 R or 42 R/min

III. ELECTRONIC EQUILIBRIUM

A. If the number of electrons entering a volume element is equal to the number leaving the element, then electronic equilibrium exists

B. This condition will exist at a depth within a medium which is at least equal to that of the maximum range of the electrons

C. Consider a medium in which the exposure in a volume element is desired (fig. 462-21)

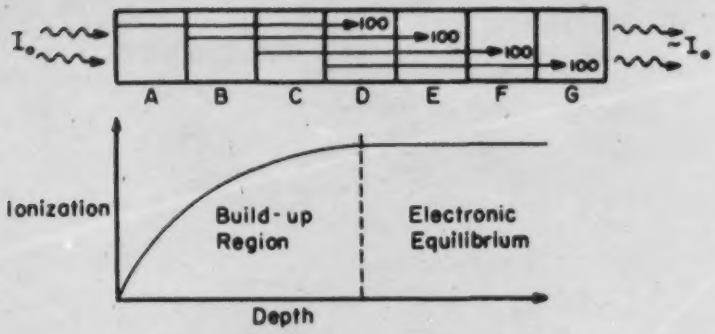


Figure 462-21. Electronic equilibrium.

1. Assuming negligible attenuation, the exposure in each square would be the same
2. Assume that there is only one interaction in each volume element
3. We need to collect all the secondary electrons produced by primary electron originating in that volume
4. Assume that the primary electron range is R and that 100 secondary electrons (ion pairs) are formed along its path
5. Square D is traversed by 4 primary electron tracks. When each segment is added together the total track length through D is R, therefore, 100 ion pairs were produced in D (the same number that originated from volume A).

IV. ION CHAMBER INSTRUMENTS

A. The standard air chamber lacks mobility. This has led to the development of "secondary standard" instruments and other instruments such as the condenser R-meter.

1. Consider mass of air when electronic equilibrium exists within the small volume element D (fig. 462-22)

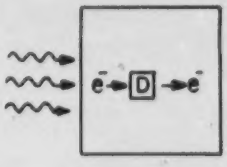


Figure 462-22. Block of air with volume element D.

2. If we "condense" the air around D and form the wall of a chamber with it, electronic equilibrium will still exist (fig. 462-23)
3. Need "air equivalent" wall

   a. $Z_{air} = 7.64$

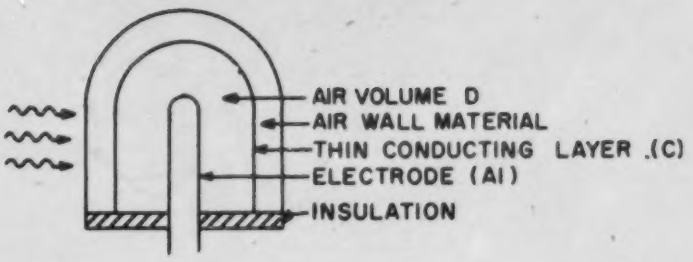


Figure 462-23. Air wall ionization chamber.

b. Walls are usually Bakelite™ (C_6H_5OH), polystyrene or nylon coated with graphite (carbon) with a center electrode of aluminum. By adjusting the electrode size and the amount of carbon, it is possible to make the chamber appear to be "air equivalent."

B. Factors contributing to poor energy response

1. Improper wall thickness

a. If the wall thickness is much too great (more than the equilibrium thickness), attenuation will occur in wall and the response will decrease
b. If the wall thickness is less than the equilibrium thickness, more electrons will leave the volume than will enter and the response will decrease

2. Non air-equivalent wall

a. The greater the difference in μ/ρ between the wall material and air, the greater will be the energy dependence of the chamber
b. Bakelite™ or plastic chamber walls are the least energy dependent since their atomic number approximates air
c. Metal is not used as a wall material, especially at low-photon energies, because of the photoelectric effect

V. X-RAY DETECTORS INVOLVED

A. Ionization chambers

B. Photographic emulsions

C. Luminescent media

D. Chemical media.

LECTURE NO. 7

TITLE: Survey Meter Time Response

PURPOSE: To study the factors influencing the time response of x-ray survey instruments

TIME: 1 hour

VISUAL AIDS: Blackboard

HANDOUTS: None

REFERENCES: Attix, Roesch and Tochilin
Radiation Dosimetry

7. SURVEY METER TIME RESPONSE

I. INTRODUCTION

In diagnostic radiographic equipment and techniques, the exposures are often short (high current, short time) and the equipment itself does not readily provide tube currents low enough to permit long (several seconds) exposure times without overloading the x-ray tube. In evaluating personnel exposure in diagnostic procedures, the x-ray equipment must be operated under "worst possible conditions" as far as kVp and beam direction are concerned. The end result of this is that a survey instrument, used to measure the instantaneous exposure rate, may not "have time" to reach an equilibrium reading during the time x ray is on. The fact that it takes time for a survey meter to reach a steady-state reading is of importance when exposure times are less than the instrument response time.

II. FACTORS INFLUENCING TIME RESPONSE

A. The inertia of the readout meter movement

1. Most survey meters use a d.c. microammeter as the readout element
2. Meter inertia is usually negligible compared to other sources of reading delay

B. The RC time constant of the circuit is R (resistance in ohms) times C (capacitance in farads)

1. It is the time required for meter to indicate (1 - 1/e) or 63 percent of its final steady-state reading

2. In ion chamber instruments (fig. 462-24)

a. C = chamber capacitance (C_h) and distributed capacitance (C_d) of associated circuitry
b. R = load resistor (in most cases)

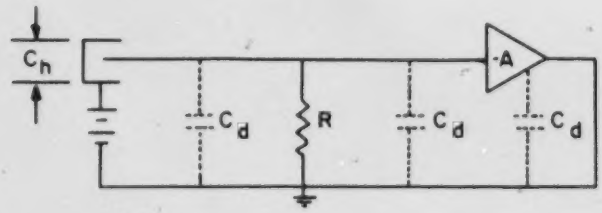


Figure 462-24. Survey meter electrical diagram.

c. Sensitivity is changed by switching in more or less load resistance

d. As a result, the time constant may be different from one range to another. R is high, often 10^8 - 10^{12} ohms, so it is important that C be low

3. In GM survey meter instruments:

   a. R and C are in the output meter circuit

      (1) The meter shunt resistance is changed to change range
      (2) As a result, time constant is uniform regardless of range
      (3) Time constant is intentionally varied by changing the capacitance in this circuit.

LECTURE NO. 8

TITLE: X-Ray Beam Factors

PURPOSE: To discuss x-ray field distribution, half-value layers and the homogeneity coefficient

TIME: 2 hours

VISUAL AIDS: Blackboard
Slide projector and slides from papers by Trout et al. (see references below)

HANDOUTS: Reprints of references by Trout et al.

REFERENCES: Atlee and Trout
A Study of Roentgen-Ray Distribution at 60-140 kVp

ICRU Report 10d

Trout, Kelley and Lucas
Determination of Half-Value Layer

Trout, Kelley and Lucas
The Second Half-Value Layer and the Homogeneity Coefficient

8. X-RAY BEAM FACTORS

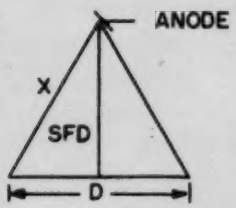
I. INTRODUCTION

The distribution of radiation across the x-ray field is not uniform because of the inverse-square law, attenuation within the target and attenuation in the plane filtration external to the x-ray tube unit.

II. INVERSE-SQUARE LAW EFFECT

A. The distance from the focal spot of the x-ray tube to various points on the useful plane field will be different

B. The magnitude of the inverse-square law effect can be calculated if the geometry is known (fig. 462-25)



SFD = source-film distance

D = field diameter

x = distance from source edge of field

Figure 462-25. Inverse-square law effect.

1. Example: Calculate the magnitude of the I.S.L. effect if SFD = 50 cm, D = 20 cm, field center exposure 100 percent

a. $x^2 = (SFD)^2 + (D/2)^2$

$= (50)^2 + (10)^2$

$= 2600$

$x = 51$ cm

b. $M = 100\ (50)^2/(51)^2$

$= 96$ percent

c. Thus there is a 4 percent reduction because of I.S.L.

III. ATTENUATION WITHIN TARGET

A. Field distribution parallel to tube axis for typical diagnostic x-ray tube (fig. 462-26)

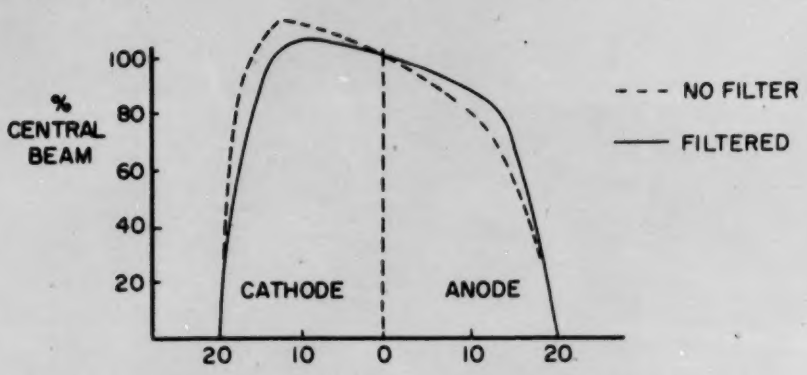


Figure 462-26. Field distribution parallel to x-ray tube axis.

B. Field distribution parallel to the tube axis falls rapidly toward anode end ("heel") of target

1. The "heel" effect is explained as follows:

   a. Not all x rays are produced at the surface of the target
   b. Electrons penetrate the surface and x rays are produced at a depth within target
   c. X rays so produced are filtered by the tungsten target resulting in a loss in intensity before they emerge from the target
   d. The thickness of tungsten increases toward the "heel" (anode end) of the target

2. The maximum intensity is not in the geometric center of field but lies on cathode side of field center
3. The decrease in intensity with added filter is less abrupt toward anode end of the tube

C. Field distribution perpendicular to tube axis (fig. 462-27)

1. The distribution is uniform across the field and drops abruptly at both edges because of the beam limiting diaphragm
2. Filtration narrows the field

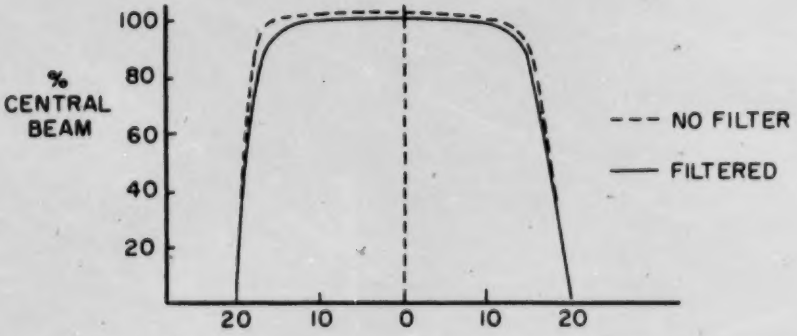


Figure 462-27. Field distribution perpendicular to x-ray tube axis.

D. Target etching

1. Etching occurs when the focal spot area is raised above its re-crystallization temperature
2. Etching occurs with normal tube loadings
3. Etching results in small "pits" in target
4. Etching increases the target filtration and narrows the field

IV. KILOVOLTAGE

A. As electron energy is increased the direction of maximum x-rav production moves toward the direction of electron flow

B. As a result, for a reflection target, the field distribution will change parallel to the tube axis (fig. 462-28)

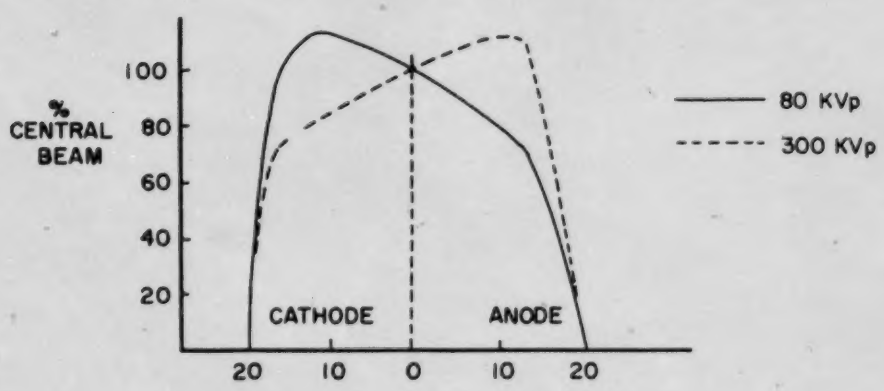


Figure 462-28. Field distribution as a function of kilovotage.

V. TARGET ANGLE

A. The more abrupt the target angle the greater the effect on field distribution (fig. 462-29)

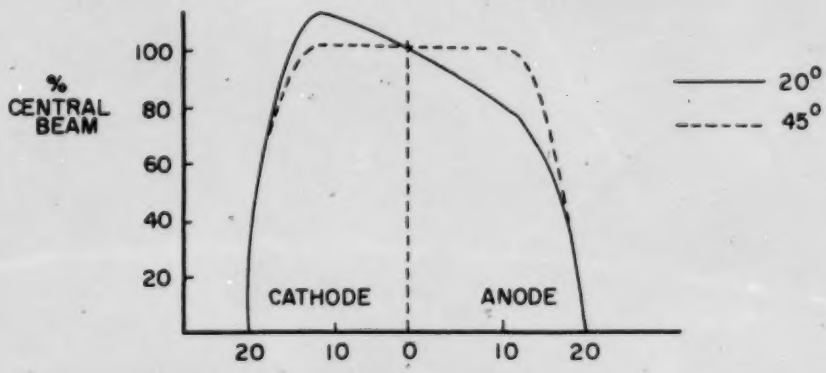


Figure 462-29. Field distribution as a function of target angle.

VI. EFFECTIVE ENERGY AND HALF-VALUE LAYER

A. For a monoenergetic x-ray beam with narrow beam geometry, the attenuation is given by:

1. $I = I_0 e^{-\mu x}$

2. $HVL = 0.693/\mu = 0.693/(\mu/\rho)\rho$

B. Effective energy

1. Most x-ray beams are heterogeneous
2. An x-ray beam with the same HVL as a monoenergetic x-ray beam is said to have the same effective energy as the monoenergetic beam
3. Effective energy is normally expressed as keV (eff.)
4. To determine effective energy:

a. Determine the HVL in some material (Al up to 150 kVp, Cu from 150-500 kVp, Pb > 500 kVp)

b. Calculate μ/ρ from $\mu/\rho = 0.693/(HVL)(\rho)$

c. From a graph of μ/ρ versus photon energy determine E for μ/ρ (fig. 462-30)

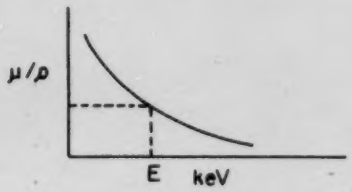


Figure 462-30. Mass attenuation coefficient versus keV.

d. Example: Assume 100 kVp with HVL = 4 mm Al

(1) $\mu/\rho = 0.693/(0.4\ cm)\ (2.7\ g/cm^3) = 0.64\ cm^2/g$

(2) E = 37 keV

C. The HVL has been chosen as the means to compare an x-ray spectrum with a monoenergetic x-ray beam

1. As kVp increases, keV (eff.) increases
2. As filtration increases, keV (eff.) increases

VII. DETERMINATION OF HVL

A. Since an x-ray beam is composed of spectrum of energies, a semilog plot of transmission versus added filter (absorber) thickness is not a straight line (fig. 462-31)

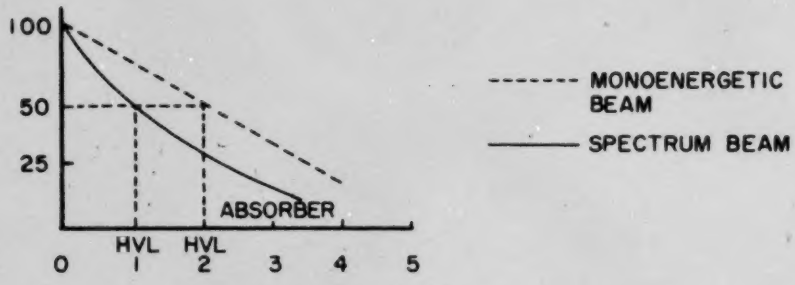


Figure 462-31. Transmission versus added absorber.

1. The slope is continually changing (HVL is changing) and μ/ρ is changing
2. The slope approaches the slope of the monoenergetic beam at high filtrations

B. Effect of measuring geometry on HVL determinations

1. Geometric variables (fig. 462-32)

   a. Diameter of field at absorber
   b. Source-absorber distance (SAD)
   c. Source-chamber distance (SCD)

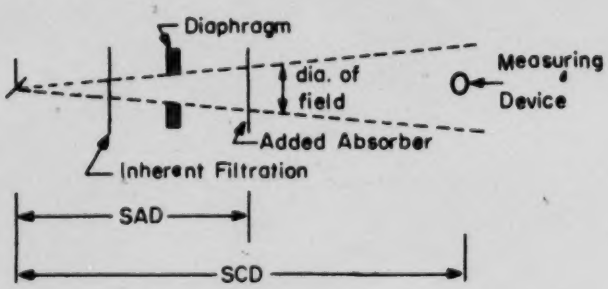


Figure 462-32. Geometric variables.

2. Good geometry

   a. Narrow beam
   b. Large SCD
   c. SAD = 1/2 SCD
   d. μ/ρ is determined under good geometry

3. Poor geometry

   a. Broad beam
   b. Thick absorber
   c. Short SCD
   d. Both unattenuated and scattered radiation are measured
   e. Build-up factor B

$$I = I_0 B e^{-\mu x}$$

4. Effect of field size (fig. 462-33)

   a. The quantity of scatter is a function of the field diameter at the added absorbers

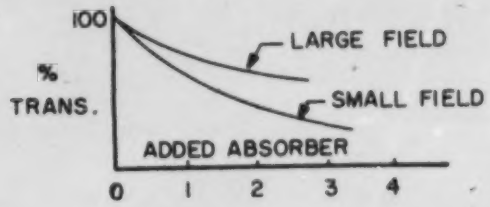


Figure 462-33. Effect of field size on measured transmission.

   b. With kVp, inherent filtration and SAD constant, the HVL decreases as the diameter of the field at the added absorbers is decreased (fig. 462-34)
   c. The effect is due to scatter from the absorbers

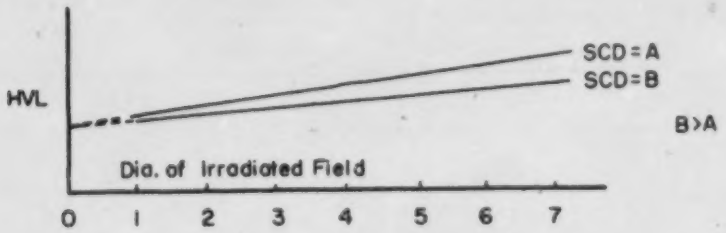


Figure 462-34. HVL versus field diameter.

5. Effect of SCD

   a. With kVp, inherent filtration and field diameter at irradiated absorber constant, SAD = 1/2 SCD, the HVL will decrease as the SCD is increased and level off at long SCD's (fig. 462-35)
   b. At long SCD's scatter from the absorbers becomes a lesser part of the total exposure

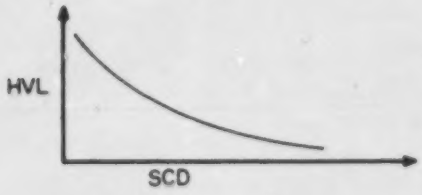


Figure 462-35. HVL versus source-chamber distance.

6. Effect of SAD

   a. With kVp, filtration, SCD and diameter of field at added

absorber constant, the HVL will decrease to minimum at SAD = 1/2 SCD (fig. 462-36)

b. The curve is symmetric about the minimum
c. The curve shape is the result of scatter from the absorber

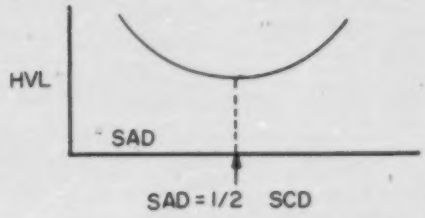


Figure 462-36. HVL versus source-absorber distance.

VIII. THE UNIQUE HVL

A. Independent of measuring geometry

B. Determined by extrapolating HVL versus field diameter to zero field diameter at absorber

1. Unique HVL is independent of geometry since the scatter is 0 at 0 field size
2. Unique HVL used to determine keV (eff.)

C. Unique HVL can be calculated from broad beam HVL if the geometry of the determination (SAD, SCD, dia. of field) is known

IX. THE SECOND HVL

A. The first HVL (1 HVL) does not adequately, in itself, specify the quality of an x-ray beam

1. The same 1 HVL can be obtained at different kVp's:

a. 200 kVp, 0.5 mm Cu, 1 HVL = 1.0 mm Cu
b. 150 kVp, 0.75 mm Cu, 1 HVL = 1.0 mm Cu

2. kVp and 1 HVL are a better description of beam quality

3. A more complete description includes kVp, 1 HVL and second HVL (2 HVL) or homogeneity coefficient

a. 1 HVL is the absorber thickness that reduces exposure from 100 percent to 50 percent.
b. 2 HVL is the absorber thickness that reduces exposure from 50 percent to 25 percent
c. The homogeneity coefficient (H) is the ratio of the 1 HVL to the 2 HVL (fig. 462-37)

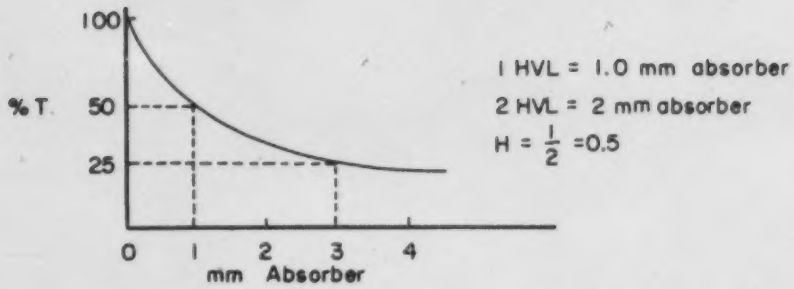


Figure 462-37. Determination of 1 HVL and 2 HVL.

(1) H = 1 HVL/2HVL < 1
(2) H_o = Unique 1 HVL/Unique 2 HVL — H_o = unique homogenity coefficient
(3) H < 1 for a heterogeneous x-ray beam
(4) H = 1 for a monoenergetic x-ray beam

X. EXAMPLE OF HALF-VALUE LAYER DETERMINATIONS

A. Aluminum transmission data at 100 kVp with two field sizes at the added absorbers were determined to be as follows:

Percent Transmission	2 cm dia field	4 cm dia field
	Added Absorber-mm Al	
100	0	0
50	1.08	1.10
25	3.40	3.46

B. What are the 1 HVL and 2 HVL for each field area?

1. 2-cm dia. field 1 HVL = 1.08 - 0 = 1.08 mm Al
2. 2-cm dia. field 2 HVL = 3.40 - 1.08 = 2.32 mm Al
3. 4-cm dia. field 1 HVL = 1.10 - 0 = 1.10 mm Al
4. 4-cm dia. field 2 HVL = 3.46 - 1.10 = 2.36 mm Al

C. What are the "unique" 1 HVL and 2 HVL?

1. Since HVL is a linear function of field diameter at the added absorbers, the "unique" (zero field) HVL can be determined by:

   a. Plotting the data and extrapolating to zero field diameter
   b. Determining the equation of the straight line and solving for zero diameter

2. Since the field diameters used were 2 and 4 cm the HVL difference between 2 and 4 cm will be equal to the HVL difference between 0 and 2 cm

   a. "Unique" 1 HVL = 1.08 - (1.10-1.08) = 1.06 mm Al
   b. "Unique" 2 HVL = 2.32 - (2.36-2.32) = 2.28 mm Al

D. What is the "unique" homogeneity coefficient?

1. H_0 = "Unique" 1 HVL/"Unique" 2 HVL

2. H_0 = 1.06/2.28 = 0.465

E. What is the effective energy of the beam in keV?

1. μ/ρ = 0.693/(1 HVL) (ρ) = 0.693/(0.106)(2.7)
   = 2.42 cm^2/g

2. From graph of μ/ρ versus keV for aluminum, keV = 22.5

LECTURE NO. 9

TITLE: Personnel Monitoring Devices

PURPOSE: To discuss the different devices used for personal monitoring

TIME: 1 hour

VISUAL AIDS: Blackboard
Film badge and holder
Pocket chamber and charger/reader
Pocket dosimeter and charger

HANDOUTS: None

REFERENCES: Attix, Roesch and Tochilin
Radiation Dosimetry

NBS Handbook 57

Ter-Pogossian
Physical Aspects of Diagnostic Radiology

Whyte
Principles of Radiation Dosimetry

9. PERSONNEL MONITORING DEVICES

I. POCKET CHAMBERS AND DOSIMETERS

A. Pocket chamber with separate charger-reader

1. Operation

   a. Chamber consists of a defined air volume and capacitor. The air volume is unsealed (fig. 462-38).

Figure 462-38. Pocket chamber.

   b. Ions produced cause capacitor to discharge (fig. 462-39)

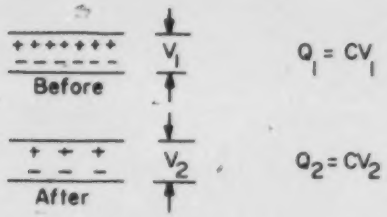


Figure 462-39. Charge on pocket chamber before and after exposure.

   c. Charge liberated $Q = Q_1 - Q_2 = C(V_1 - V_2) = C\Delta V$

   d. If the chamber volume is known, exposure,

$$X = \Delta Q/v = C\Delta V/v$$

2. Cost

   a. Chamber--$12 each for 0-200 mR chamber
   b. Charger-reader--$575 each

B. Direct reading pocket dosimeter

1. Operation

a. Similar to pocket chamber but dosimeter includes a quartz fiber electrometer and optical system. The air volume is sealed (fig. 462-40).

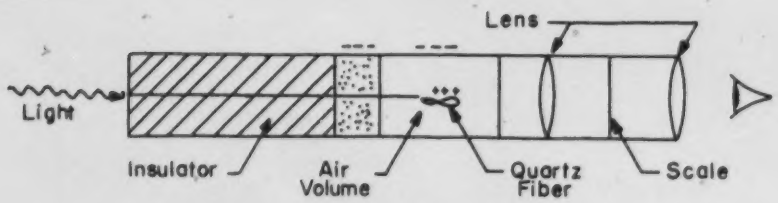


Figure 462-40. Pocket dosimeter.

b. As the chamber discharges, the quartz fiber "moves" and the exposure is read on the scale in mR or R

2. Cost

a. Chamber-high energy 0-200 mR--$40 each
b. Chamber-low energy 0-200 mR--$75 each
c. Charger--$50 each

C. Disadvantages

1. Chambers are subject to mechanical damage that can lead to false reading
2. Leakage can increase reading
3. Readings do not provide a permanent record
4. They are energy dependent
5. They have a limited range

D. Advantages

1. Chambers are reusable
2. The direct reader can be read "immediately"
3. They provide a daily check on exposure

II. FILM

A. Operation

1. A film emulsion consists of AgBr suspended in gelatin (fig. 462-41)

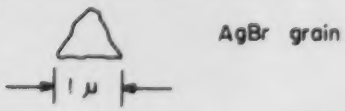


Figure 462-41. AgBr grain.

2. The photons interact with the emulsion and the resulting photoelectrons interact with the AgBr crystals
3. Photoelectron renders grain susceptible to developer (latent image) and developer supplies electrons to convert silver ions to free silver

$$(Ag^+) \quad (Br^-) \quad + e^- \rightarrow Ag + Br^-$$

B. Characteristics

1. Single hit phenomena (direct exposure)

   a. It takes only one photon (X or ϒ) "hit" to produce the latent image in a grain
   b. Therefore the process is not rate dependent
   c. There is a linear relation between response (density) and exposure (fig. 462-42)

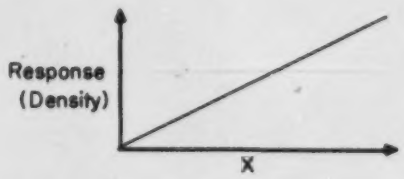


Figure 462-42. Film response versus exposure.

   d. For light (intensifying screens) exposures it requires several photons to produce the latent image, therefore, this process is rate dependent

2. Advantages of film:

   a. It can integrate exposure over a long time
   b. Relatively low in cost ($0.50 - $2.00)
   c. Provides a permanent record
   d. It is rate independent (within limits)
   e. It is easy to use
   f. It is relatively rugged

3. Disadvantages of film:

   a. Processing time is required
   b. Response influenced by humidity and chemical actions

4. Sensitivity

Source	Min. Sensitivity
Diagnostic x rays	∿ 5 mR
ϒ or high energy x rays	∿ 20 mR

5. Energy dependence (fig. 462-43)

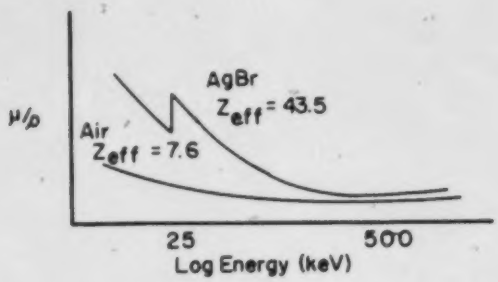


Figure 462-43. Mass attenuation coefficient versus keV for film and air.

a. AgBr has greater sensitivity than air at lower energies
b. Relative sensitivity is the reciprocal of the exposure required to produce a certain density (1.0) (fig. 462-44)

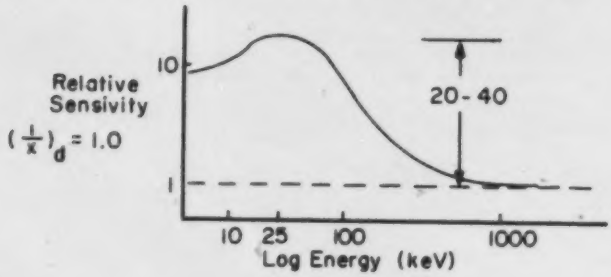


Figure 462-44. Relative film sensitivity versus keV.

(1) If X = 1R for d = 1.0 at 25 keV, then 20-40 R are needed for d = 1.0 at 1 MeV
(2) Rule of thumb--keV = 1/2 kVp for a heavily filtered x-ray beam
(3) Peak in the curve corresponds to the K-edge of AgBr

6. Film density

a. A densitometer is used to measure film density. It measures the light transmitted through the film (fig. 462-45)

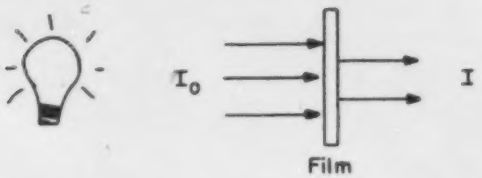


Figure 462-45. Transmission of light through film.

b. Transmission $T = I/I_0$

c. Density = $\log_{10}/1T = \log_{10}/I_0/I$

Transmission		Density
1/10	(10^{-1})	$\log_{10}10 = 1$
1/100	(10^{-2})	$\log_{10}100 = 2$
1/1000	(10^{-3})	$\log_{10}1000 = 3$
1/000000	(10^{-6})	$\log_{10}10^6 = 6$

d. Density ∝ number of grains developed

7. Sensitometric curves

a. Used to relate density to exposure (X)
b. Linear relation between density and exposure (fig. 462-46)

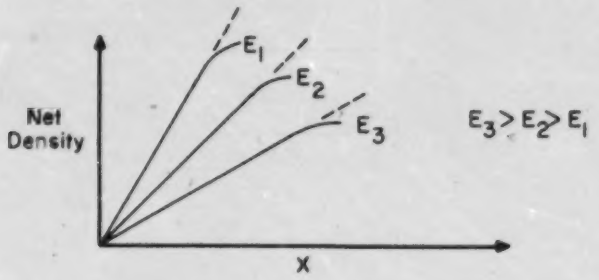


Figure 462-46. Film response versus exposure for several photon energies.

(1) Net density is the density of the exposed film minus the density of the unexposed film
(2) A family of curves results because of energy dependence of the AgBr
(3) The deviation from linear at high exposures is due to photoelectrons acting on grains which already have produced the latent image ("run out of film")

c. H & D curve (Hurter and Driffield 1890)--net density versus log X (fig. 462-47)

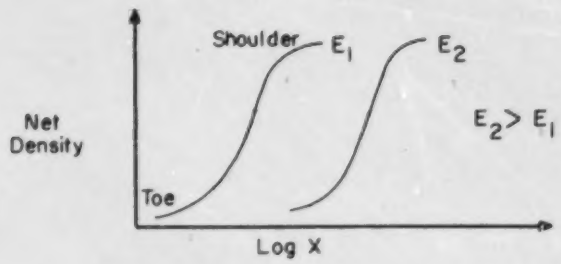


Figure 462-47. H and D curves.

(1) The shape of the curve remains the same as function of energy but the curve is shifted on exposure axis
(2) H and D curves are most often used to represent the response of film

d. Log net density versus log X (fig. 462-48)

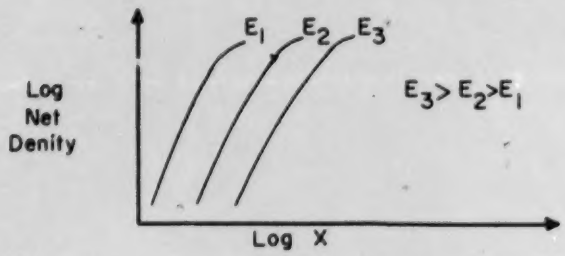


Figure 462-48. Log net density vervus log exposure.

(1) This presentation is useful when a wide range of exposures are of interest
(2) It is easier to read (graphically) extreme densities

8. For a given emulsion or film type the shape of the curves is a function of:

a. Developing time
b. Developer temperature
c. Developer condition

C. Calibration and use

1. Procedure

a. Calibration films, control and badge films are taken from the same batch (emulsion number)
b. All films are processed together

2. Film badge

a. Serves as a holder for the film
b. It contains several filters

(1) Consider two films, one exposed to heavily filtered 50 kVp x rays and one to radium gamma rays (1 MeV)
(2) If both films are assumed to have been exposed by the same energy photons, a gross over or under evaluation of the exposure from one of the films will be obtained (fig. 462-49)
(3) Filters (usually) in the film badge holder compensate for the energy dependence of the film

(a) Open window, no filter, film density is due primarily to low energy x rays

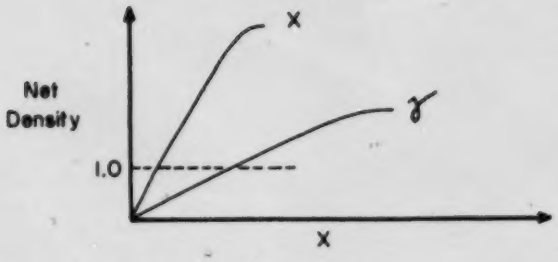


Figure 462-49. Net density versus exposure for film exposed to x rays and gamma rays.

(b) Filter areas absorb low energy x rays and transmit higher energies. This permits evaluation of energy and the total exposure.

(4) Film works on the photoelectric effect

$$\propto Z^n/E^x \quad \text{so as } E \downarrow, d \uparrow$$

III. THERMOLUMINESCENT DOSIMETERS

Thermoluminescent materials are being used for personnel monitoring to either replace or augment personal monitoring film. These materials will be discussed in a later lecture.

LECTURE NO. 10

TITLE: Chemical Dosimetry

PURPOSE: To discuss several chemical dosimeters and their theory of operation

TIME: 1 hour

VISUAL AIDS: Blackboard

HANDOUTS: None

REFERENCES:

Attix, Roesch and Tochilin
Radiation Dosimetry

Chorzempa
Ionizing Radiation and its Chemical Effects: A Historical Study of Chemical Dosimetry 1902-1962

Hine and Brownell
Radiation Dosimetry

Spiers and Reed
Radiation Dosimetry

10. CHEMICAL DOSIMETRY

I. INTRODUCTION

The basis for chemical dosimetry is the determination of dose by the magnitude and kind of a chemical change that is produced in a medium. Most chemical dosimeters involve reactions produced in aqueous solutions and have a principal use in the high dosage range.

II. DESIRABLE CHARACTERISTICS

A. High sensitivity

B. Accuracy

C. Reproducibility, linearity

D. Stable - time and temperature

E. Wide range of physical forms

F. Inexpensive

G. Energy independent

H. Tissue equivalent

III. BASIC CONSIDERATIONS

A. Absorption of energy in a liquid system produces a definite chemical reaction

1. Consider the chemical change
2. Relate the energy deposited and ionization produced to a chemical effect
3. "Good" or "bad" effects in a physical system can result from chemical change
4. The quantity of chemical change should increase linearly with dose

B. Reaction yield

1. Expressed as number of molecules of specified substance formed or destroyed per ion pair produced

2. G value - number of molecules altered chemically per 100 eV absorbed

   a. Value of 100 - 200 is required for doses of 100 - 1,000 rad
   b. Chain reactions are normally required for high G values

3. Use is limited by the chemical method of analysis used to detect the newly formed compound

4. Absorbed dose given by:

   a. $D_{rad} = (M)\ (9.64 \times 10^8)/(G)\ (P)\ \rho$

      (1) M = number of moles of ion product P
      (2) (G) (P) = G value of ion product P
      (3) ρ = density of system

5. The foremost problem is that a very pure system is required

C. Irradiation of water

1. Some products formed are free radicals (contain unpaired electron in outer shell)
2. A primary chemical bond is represented as the sharing of two electrons between constituent atoms
3. Radiolysis of water

   a. $H_2O \rightarrow H_2O^+ + e^-$

   b. $H_2O^+ \rightarrow H^+ + OH\cdot$

   c. $e^- + H_2O \rightarrow H_2O^-$

   d. $H_2O \rightarrow H\cdot + OH^-$

   e. Overall $H_2O \rightarrow H\cdot + OH\cdot$

IV. TYPICAL CHEMICAL DOSIMETERS

A. Ferrous sulfate (Fricke Dosimeter)

1. Ferrous ions (Fe^{++}) are converted to ferric ions (Fe^{+++})
2. Chemical reactions

   a. $H\cdot + O_2 \rightarrow HO_2$

   b. $FE^{++} + OH\cdot \rightarrow Fe^{+++} + OH^-$

   c. $Fe^{++} + HO_2^{\cdot} \rightarrow Fe^{+++} + HO_2^-$

   d. $HO_2^- + H^+ \rightarrow H_2O_2$

   e. $H_2O_2 + Fe^{++} \rightarrow Fe^{+++} + OH\cdot + OH^-$

3. The quantity of Fe^{+++} is determined by absorption spectroscopy or chemical titration
4. The useful dose range is 10^3 - 10^5 rads (G < 20)

B. Ceric sulfate

1. Reduction of ceric (Ce^{4+}) to cerous ion (Ce^{3+})
2. It is very sensitive to impurities
3. The useful range is 10^4 - 10^8 rad (G > 5)

C. Chlorinated hydrocarbons

1. Production of HCL is determined

2. It is a high yield reaction and suitable for lower doses (> 20 rad)
3. A dye indicator is used to determine the quantity of HCL produced

LECTURE NO. 11

TITLE: Thermoluminescent Dosimeters

PURPOSE: To present the fundamentals of thermoluminescent phosphors and their uses as ionizing radiation dosimeters

TIME: 1 hour

VISUAL AIDS: Blackboard
E. G. & G. thermoluminescent dosimeters

HANDOUTS: None

REFERENCES:

Attix, Roesch and Tochilin
Radiation Dosimetery

Cameron, Suntharalingam and Kenney
Thermoluminescent Dosimetry

Fowler
Solid State Dosimetry

11. THERMOLUMINESCENT DOSIMETERS

I. INTRODUCTION

The basis for use of some materials as dosimeters is their ability to store energy imparted to them by radiation. The release of this energy in the form of light may be controlled and measured and the quantity of light is approximately a linear function of absorbed energy.

II. THEORY

A. Definitions

1. Fluorescence - glow of certain crystals immediately following exposure to electromagnetic or particulate radiation
2. Phosphorescence - a time lag between exposure and emission of light
3. Thermoluminescence - electrons trapped at metastable levels in crystal defects are freed by thermal stimulation resulting in release of light
4. Phosphors - crystals exhibiting any of the above characteristics

B. Physical model of a phosphor (fig. 462-50)

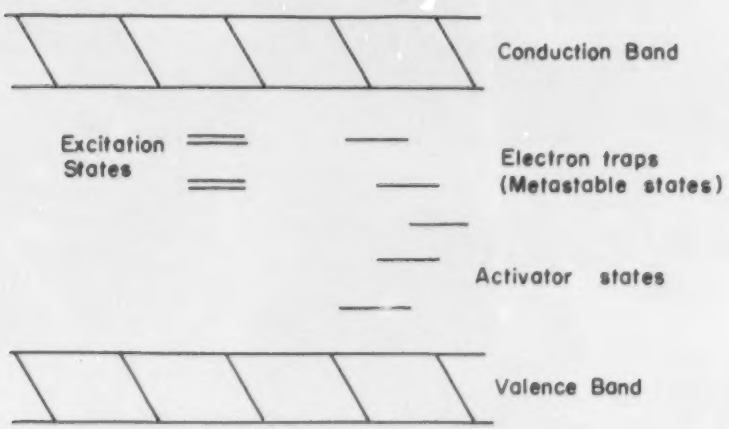


Figure 462-50. Physical model of a phosphor.

1. Based on energy band scheme of a pure insulator
2. Impurity atoms produce metastable states between valence and conduction bands
3. Electrons raised to conduction band may become associated with one of these energy states and said to be "trapped"

III. CHARACTERISTICS OF TL MATERIALS

A. Consider CaF_2:Mn, LiF (TLD-100), $CaSO_4$:Mn

B. Criteria

1. Sensitivity (x and γ)

   a. Lower limit of LiF is 10 mR ± 25 percent (requires special readout)
   b. CaF_2 and $CaSO_4$ are more sensitive with $CaSO_4$:Mn in μR range
   c. Factors determining detectable limits

      (1) Detector (PM tube) dark current
      (2) Nonradiation induced TL
      (3) Thermal interference from heater
      (4) Wavelength of emitted light

2. Response

   a. LiF is linear from 10^{-2} -10^3 R, supra-linear above 10^3 R, and useful to 10^5 R
   b. CaF_2 is approximately linear to 10^6 R
   c. $CaSO_4$ is linear to 10^3 - 10^4 R

3. Rate dependence

   LiF is independent of rate to 10^8 R/sec

4. Energy dependence (fig. 462-51)

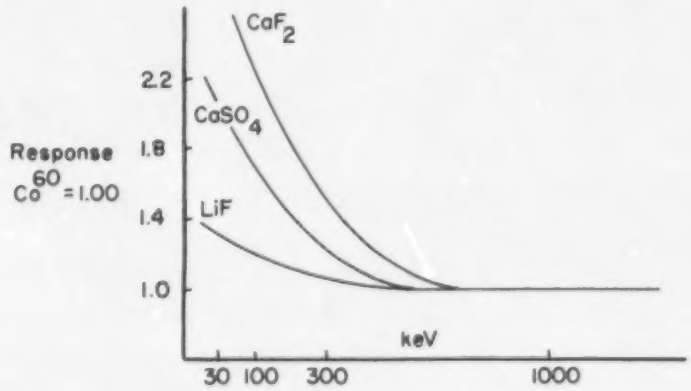


Figure 462-51. Energy dependence of TL phosphors.

   a. LiF response at 30 keV is only 25 percent greater than that at 1.2 MeV
   b. CaF_2 response ↶ 13 times greater at 40 keV than at 1.2 MeV
   c. $CaSO_4$ response ↶ 11 times greater at 40 keV than at 1.2 MeV
   d. Filters are used to "flatten" response

5. Energy storage capability (decay)

   a. LiF fades 5 percent/yr at 22° C, 15 - 20 percent/yr at 37° C
   b. CaF_2 fades more rapidly than LiF
   c. $CaSO_4$ fades fast

IV. EQUIPMENT

A. Readout

1. Heat phosphor
2. Measure light emitted
3. Display results

   a. Digital system
   b. Strip chart recorder - light (PM current) versus temperature (time)

B. Miscellaneous

1. Annealing oven (50 - 450° C)
2. Phosphor dispensor

C. TL material

V. LiF MATERIAL IN POWDER FORM

A. Characteristics

1. White crystalline powder
2. Inert
3. Nontoxic

B. Sieve (80 - 200 mesh)

C. Anneal

400° C for 1 hour, 80° C for 24 hours

D. Expose

E. After exposure, dispense and read samples

1. Samples are generally 20 - 50 mg
2. Readout time is 6 - 60 sec at 300° C
3. 1 - 3 percent reproducibility for X > 1 R in lab use

F. Precautions in use

1. Different equipment will not produce the same sensitivity
2. Recalibrate powder after use
3. Dispense powder accurately
4. Maintain uniform crystal distribution in heating pan

VI. LiF and CaF_2:Mn DOSIMETERS

A. Evacuated (or inert gas filled) glass envelope

1. TL powder is bonded to support or hot pressed to support
2. Tungsten filament heating element is used

B. Glass or plastic tubes

1. Heated by induction
2. Can be small (approx. 1 mm dia. x 6 - 12 mm long)

C. Hot-press material (no outer container)

D. Advantages of dosimeters over loose powder

1. Easy and convenient readout
2. Easy to handle
3. No need to sieve or clean
4. No phosphor loss
5. Lower useful dose range
6. Easy to incorporate in dosimeter (energy compensating) holders
7. Easy to sterilize (glass)

LECTURE NO. 12

TITLE: Correlation of Exposure and Absorbed Dose

PURPOSE: To determine the energy absorbed in matter from an exposure to x rays

TIME: 1 hour

VISUAL AIDS: Blackboard

HANDOUTS: None

REFERENCES:

Attix, Roesch and Tochilin
Radiation Dosimetry

ICRU Report 10b

ICRU Report 19

Johns and Cunningham
The Physics of Radiology

Ter-Pogossian
Physical Aspects of Diagnostic Radiology

Whyte
Principles of Radiation Dosimetry

12. CORRELATION OF EXPOSURE AND ABSORBED DOSE

I. INTRODUCTION

The biological effect that ionizing radiation is capable of producing is due to the energy that is absorbed in tissue. Exposure, measured in roentgens, tells nothing about absorbed energy. The air exposure must be converted to an absorbed dose (in rads) to evaluate the biological effect.

II. UNITS AND CONSTANTS

A. Exposure $X = dQ/dm$

1. Defined in air for x and γ radiation only
2. Unit of exposure is the roentgen (R)

   a. $1\ R = 2.58 \times 10^{-4}$ C/kg air
   b. 1 R = 1 esu/0.001293 g air
   c. $1\ R = 1\ esu/cm^3$ dry air at STP

B. Absorbed dose $D = d\bar{\epsilon}/dm$

1. Defined in any material for any ionizing radiation
2. Unit of absorbed dose is the rad

   a. $1\ rad = 10^{-2}$ J/kg
   b. 1 rad = 100 ergs/g

C. Constants

1. Change of an electron

   a. 1.6×10^{-19} coulombs
   b. 4.8×10^{-10} esu

2. Electron volt

   a. 1.6×10^{-19} joule/eV
   b. 1.6×10^{-12} erg/eV

3. Mean average energy ($\bar{W}$) expended by electrons in producing an ion pair

   a. $W_{air} = 33.7$ eV/ion pair
   b. $W_{air} = 5.4 \times 10^{-11}$ erg/ion pair
   c. $W_{air} = 5.4 \times 10^{-18}$ joule/ion pair

III. ABSORBED DOSE IN AIR

A. Relation between the roentgen and the rad:

1. $$1\ R = \left[\frac{2.58 \times 10^{-4} C}{Kg}\right]\left[\frac{33.7\ eV}{1P}\right]\left[\frac{1\ 1P}{1.6 \times 10^{-19} C}\right]\left[\frac{1.6 \times 10^{-19} J}{eV}\right]\left[\frac{1\ rad}{10^{-2} J/Kg}\right] = 86.95 \times 10^{-2}\ rad$$

2. 1 R = 0.87 (rad)

B. Relation between dose and exposure:

1. $D_{air} = X\ (R)\ (0.87\ rad/1\ R)$

   $D_{air} = 0.87\ X\ (rad)$

IV. ABSORBED DOSE IN MATERIALS OTHER THAN AIR

A. Calibrated ion chamber used (fig. 462-52)

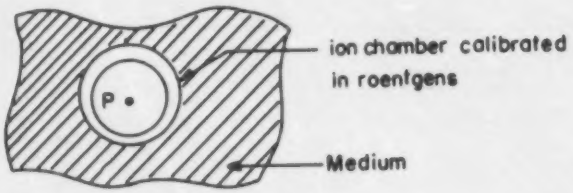


Figure 462-52. Determination of absorbed dose.

1. We want to determine absorbed dose at P
2. Place an ion chamber in the medium with the chamber center at P
3. Since the medium and the air in the ion chamber are exposed to the same radiation field, the fraction of incident energy absorbed in each case is proportional to the mass energy absorption coefficient μ_{en}/ρ of the medium and of air

   a. $D_{med}/D_{air} = (\mu_{en}/\rho)_{med}/(\mu_{en}/\rho)_{air}$

   b. $D_{air} = 0.87\ X$

   c. $D_{med} = 0.87 \times (\mu_{en}/\rho)_{med}/(\mu_{en}/\rho)_{air}$

   d. $f = 0.87\ (\mu_{en}/\rho)_{med}/(\mu_{en}/\rho)_{air}$

   e. $D_{med} = f\ X$ rads

4. Example: An air-wall chamber placed in muscle tissue reads 1 R when exposed to 100 keV photons. What is absorbed dose?

a. $D_{muscle} = (f_{muscle})\ (X)$

$= (0.948)\ (1)$

$= 0.948$ rad

B. Calibrated chamber not available

1. Use a chamber of known volume and wall composition
2. The chamber must satisfy Bragg-Gray cavity theory:

   a. Secondary electron equilibrium must be maintained (equilibrium wall thickness)
   b. Only a small fraction of the secondary electron energy is dissipated in cavity (cavity must be small)
   c. There must be negligible photon absorption by the cavity (particles set in motion in cavity arise from interactions in chamber wall)

3. If the cavity satisfied Bragg-Gray theory, the dose in the chamber wall is:

   a. $D_w = S_a^w D_a$ where a refers to the air cavity

   b. Since different materials are ionized to different degrees by the same energy electrons, an electron of a given energy produces a different number of ions in the gas than in an equal mass of wall material. S_a^w expresses the ratio between these two numbers and is called the stopping power ratio.

   $$S_a^w = \frac{\text{energy imparted to unit mass of wall material by electrons}}{\text{energy imparted to unit mass of air by same electron flux}}$$

   c. If J_a = number of ion pairs produced per gram of air and W_a = the average energy required to produce an ion pair then:

      (1) $D_a = J_a W_a$

          (a) J_a = ion pairs/g

          (b) W_a = ergs/ion pair

      (2) $\therefore D_w = S_a^w J_a W_a$

      (3) If the wall material is air $S_a^w = 1$ and $D_w = D_a = J_a W_a$

      (4) Example: Let Q = charge collected in esu and v = chamber air volume in cm^3

          (a) $J_a = \frac{Q\ (esu)\ (1\ ion\ Pair)\ (1\ cm^3)}{v\ (cm^3)\ (4.8 \times 10^{-10}\ esu)\ (0.001293g)}$

          $= Q/v\ (1.6 \times 10^{12}\ ion\ pair/g)$

          (b) for air $X = Q/v$

          (c) $J_a = (X)\ (1.6 \times 10^{12}\ ion\ pair/g)$

(d) $D_a = (X)\ (1.6 \times 10^{12}\ \text{ion pair/g})\ (5.4 \times 10^{-11}\ \text{erg/ip})$
$= (X)\ (0.87 \times 10^{2}\ \text{ergs/g})$
$= 0.87\ X\ \text{rad}$

d. The energy absorbed in the medium may be determined from that absorbed in the cavity wall (since cavity is small) by the ratio of the mass energy absorption coefficients

$D_m = D_w\ (\mu_{en}/\rho)_m/(\mu_{en}/\rho)_w$

e. Another means is to insert a Bragg-Gray cavity in the material (same as letting the medium replace chamber wall)

(1) $D_w = S_a^w D_a$

(2) $w \rightarrow m$

(3) $D_m = S_w^m D_a$

LECTURE NO. 13

TITLE: X-Ray Shielding

PURPOSE: To present methods for the determination of protective barrier thickness for x-ray installations up to 10 MeV

TIME: 1 hour

VISUAL AIDS: Blackboard

HANDOUTS: None

REFERENCES: Braestrup and Wyckoff
Radiation Protection

ICRP Publication 15

ICRP Publication 21

NBS Handbook 93

NCRP Report 33

NCRP Report 34

NCRP Report 35

NCRP Report 36

NCRP Report 39

Radiological Health Handbook

13. X-RAY SHIELDING

I. INTRODUCTION

A. Narrow beam attenuation of a monoenergetic x-ray beam can be expressed as:

$$I = I_0 e^{-\mu x}$$

Where: I_0 = initial intensity at point of interest

I = intensity at point of interest after attenuating material placed in beam
e = base of natural logarithm
μ = linear absorption coefficient of attenuating material
x = thickness of attenuating material

B. Broad beam attenuation of a monoenergetic x-ray beam can be expressed as:

$$I = I_0 B e^{-\mu x}$$ Where: B = buildup factor

C. For a monoenergetic x-ray beam, it is a relatively simple matter to compute the thickness of material necessary to reduce the intensity at a point to a given level

D. However, when designing the shielding requirements for x-ray installations, these simple mathematical relationships cannot be applied

E. Factors determining the thickness of protective barrier necessary to reduce the x-ray exposure to a given level depend upon the:

1. Quality of radiation produced
2. Quantity of radiation produced in a given time period
3. Distance from x-ray tube to area of interest
4. Degree and nature of occupancy of the area
5. Type of area
6. Material to be used

II. DEFINITIONS

A. Protective barrier: barrier of attenuating materials used to reduce radiation exposure.

B. Primary protective barrier: barrier sufficient to attenuate the useful beam to the required degree.

C. Secondary protective barrier: barrier sufficient to attenuate stray radiation to the required degree.

D. Stray radiation: radiation not serving any useful purpose. It includes leakage and scattered radiation.

E. Controlled area: a defined area in which the occupational exposure of personnel to radiation or to radioactive material is under the supervision of an individual in charge of radiation protection. (This implies that a controlled area is one that requires control of access, occupancy, and working conditions for radiation protection purposes.)

F. Uncontrolled area: all areas not specified as being controlled.

G. Diagnostic-type protective tube housing: x-ray tube housing so constructed that leakage radiation measured at 1 meter from the source cannot exceed 100 mR in 1 hour when the tube is operated at its maximum continuous rated current for the maximum rated tube potential.

H. Therapeutic-type protective tube housing (less than 500 kV): x-ray tube housing so constructed that the leakage radiation at a distance of 1 meter from the source does not exceed 1 roentgen in an hour when the tube is operated at its maximum rated tube potential.

I. Occupancy factor (T): the factor by which the workload should be multiplied to correct for the degree or type of occupancy of the area in question.

J. Use factor (U): fraction of the workload during which the radiation under consideration is directed at a particular barrier.

K. Workload (W): the use of an x-ray machine expressed milliampere minutes per week.

III. DETERMINATION OF PROTECTIVE BARRIER THICKNESS

A. Primary protective barrier requirements

It has been found experimentally that:

1. The transmission of x ray through thick barriers is closely related to the peak voltage of the x-ray tube
2. Barrier thickness at a given kV is essentially independent of changes in HVL caused by the added filtration in the machine
3. At any given kV and with minimum added filtration, the exposure rate produced by any x-ray machine is nearly a constant when expressed in terms of roentgens per mA-min at a distance of 1 meter

B. For purposes of determining barrier thicknesses, attenuation curves have been determined for various tube voltages and attenuating materials

1. The ordinate of the attenuation curve is the transmitted exposure per mA-min at a reference distance of 1 meter and is given the symbol K
2. To compute the required barrier thickness for any set of parameters, determine allowed value of K and find the corresponding thickness on the appropriate attenuation curve
3. The value of K is computed from:

$$K_{ux} = \frac{P(d_{pri})^2}{WUT}$$

Where: K_{ux} = R/mA - min at 1 meter

P = maximum permissible exposure for design purposes: controlled areas = 0.1 R/wk, uncontrolled areas = 0.01 R/wk

d_{pri} = distance from x-ray target to area meters

W = workload, mA-min/wk

U = use factor

T = occupancy factor

C. If materials for which no attenuation data are available are to be used, their equivalents can be determined, to a first approximation, on the basis of their density

Example: 2.5 cm (1 in.) sand plaster 1.54/2.35 = 1.6 cm (0.65 in.) concrete

D. Secondary protective barrier

1. Barriers that are exposed only to leakage and scattered radiation
2. Since leakage and scatter may be of significantly different qualities, their barrier requirements must be computed separately
3. Scattered radiation. For design purposes it may be assumed that:

   a. The ratio, a, of 90° scattered exposure to incident exposure is 10^{-3} up to 3 MeV
   b. The 90° scattered radiation generated by a useful beam produced at a potential of 500 kV and below is, to a first approximation assumed to have the same average energy as the useful beam
   c. The 90° scattered radiation generated by a useful beam produced at a potential greater than 500 kV is, to a first approximation, equivalent in energy distribution to x rays generated by a potential of 500 kV regardless of the kilovoltage of the useful beam
   d. The scattered exposure is a linear function of the field area, F, at the scatterer
   e. For tube potentials of 500 kVp or less, the value of K is computed from:

$$K_{ux} = \frac{P}{a\ W\ T} (d_{sca})^2 (d_{sec})^2 \frac{400}{F}$$

Where: K_{ux} = R/mA - min at 1 meter

P = maximum permissible exposure for design purposes

a = ratio of scatter to incident exposure (10^{-3})

W = workload, mA - min/wk

T = occupancy factor

d_{sca} = distance from radiation source to scatterer, meters

d_{sec} = distance from radiation source to area, meters

F = area of useful beam at scatterer, cm^2

f. For tube potentials of 1, 2 and 3 MeV the equation is modified, due to the higher output, by multiplying the right-hand side by 1/20 for 1 MeV, 1/300 for 2 MeV, and 1/700 for 3 MeV

4. Leakage radiation

a. The leakage radiation is highly filtered. The number of half-value layers required in the secondary barrier for leakage radiation depends upon:

(1) The tube housing type
(2) Tube maximum operating potential
(3) Weekly operating time
(4) Distance to occupied area
(5) Occupancy of area
(6) Permissible exposure per week

b. The transmission factor for a diagnostic-type protective tube housing is given by

$$B_{1x} = \frac{(P)\ (d_{sec})^2\ (600I)}{W\ T}$$

and for therapeutic-type protective tube housing 500 kVp and below by

$$B_{1x} = \frac{(P)\ (d_{sec})^2\ (60I)}{W\ T}$$

where P, d_{sec}, W and T are as defined previously, B_{1x} is the transmission factor and I is the maximum continous tube current

c. The leakage barrier thickness, S_L, is then computed by S_L = N (HVL) where N is the number of half-value layers corresponding to a transmission of B_{1x}, and HVL is the numerical value of the half-value layer

E. Total secondary barrier requirements

1. If the required barriers for leakage and scattered radiation are found to be approximately the same, one HVL should be added to the larger one to obtain the required total secondary barrier thickness
2. If the two differ by at least three HVL's, the thicker of the two will be adequate

F. Sample calculation of useful beam and secondary protective barrier (to be selected by instructor based on class interest).

SHIELDING DESIGN PROBLEM SET

GIVEN:

1. The attached plan (fig. 462-53) of a proposed installation.
2. The building is a single-story structure on grade.
   a. No basement--earth fill
   b. Roof above (12' floor to roof level) with T = 1/16 noncontrolled.
3. A 200 kVp, 30 mA therapeutic x-ray unit is to be installed.
4. The x-ray tube will be located as shown on the plan.
5. The useful beam will be directed at the floor (U = 1) and north wall (U = 1/4) only.
6. W = 10,000 mA - min/wk.
7. Occupancy factors as shown on the plan (C = controlled area, NC = noncontrolled area).
8. Broad beam lead attenuation data.
9. HVL versus percent transmission data.
10. The HVL for 200 kVp is 0.48 mm Pb.

REQUIRED: Compute, in lead, the shielding required for this installation.

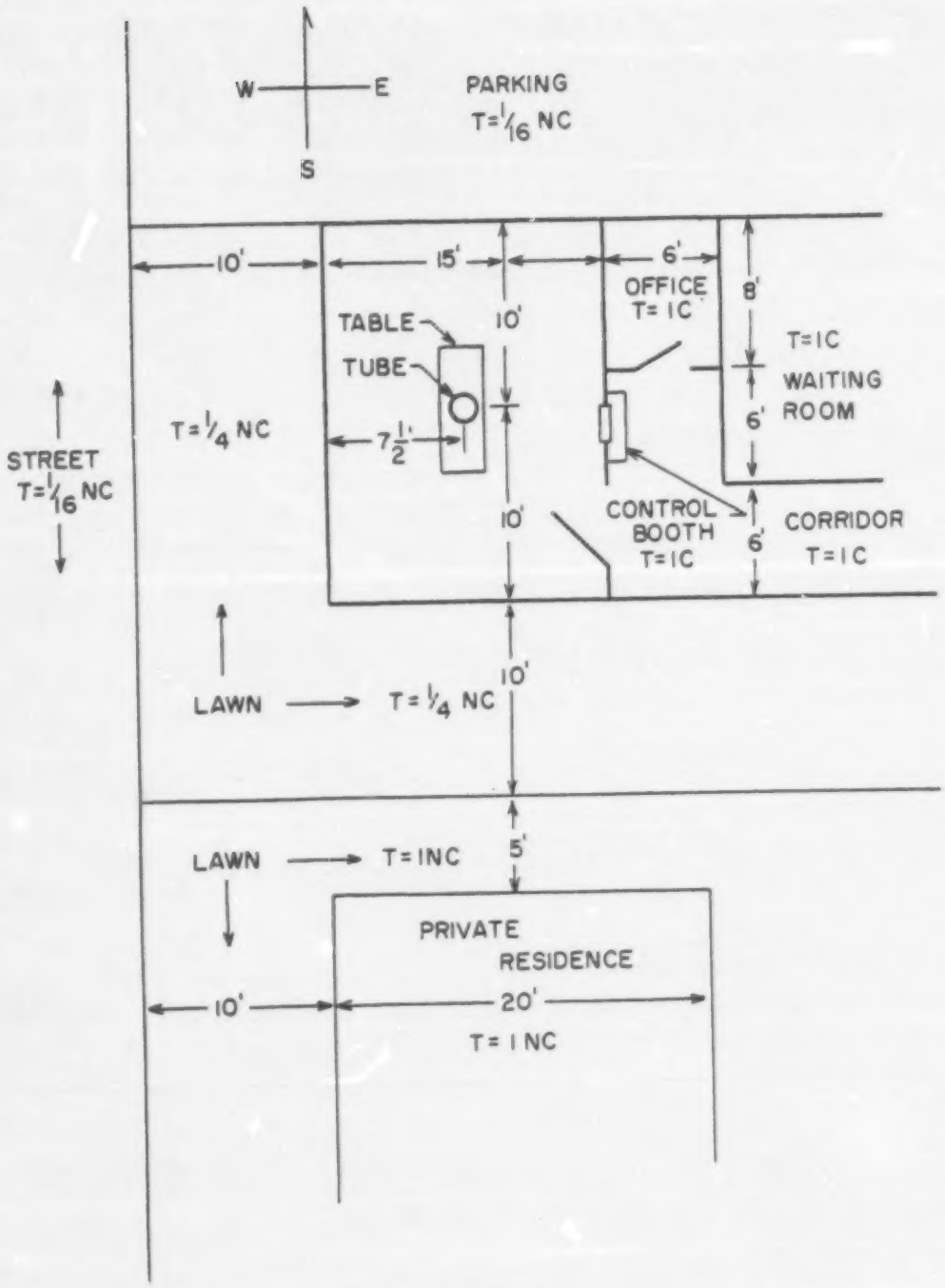


Figure 462-53.

ANSWERS TO SHIELDING DESIGN PROBLEM SET

1. Type and degree of adjacent area occupancy

Area	Type/Degree	Design Max. mR/wk
Parking, N	Noncontrolled / 1/16	160
Lawn, W & S	Noncontrolled / 1/4	40
Street, W	Noncontrolled / 1/16	160
Private lawn, S	Noncontrolled / 1	10
Residence, S	Noncontrolled / 1	10
Roof	Noncontrolled / 1/16	160
Corridor, control	Controlled / 1	100
Office, waiting room		

2. Shielding calculations

   a. North wall

      (1) Primary barrier. P = 0.01 R/wk, d = 10' (3.05 m),

      W = 10,000 mA - min/wk, U = 1/4, T = 1/16

      $K = (0.01)\ (3.05)^2 / (10^4)\ (1/4)\ (1/16) =$
      $0.000595 \rightarrow 3.3$ mm Pb

      (2) Secondary barrier, d_{sca} = 0.5 m, I = 30 mA, F = 400 cm^2

      $$\text{Scatter } K = \frac{0.01}{(10^{-3})\ (10^4)\ (1/16)} \qquad \frac{(3.05)^2\ \ (0.5)^2}{}$$
      $$= 0.037 \rightarrow 1.1 \text{ mm Pb}$$

      $$\text{Leakage } B = \frac{(0.01)\ (3.05)^2\ (60)\ (30)}{(10^4)\ (1/16)}$$
      $$= 0.27 \rightarrow 1.9 \text{ HVL} \rightarrow 0.91 \text{ mm Pb}$$

      Total secondary 1.1 + 0.48 = 1.58 mm Pb

   b. East wall and door

      (1) Secondary scatter, P = 0.1 R/wk, d_{sec} = 7 1/2' (2.29 m)

      W = 10,000 mA - min/wk, T = 1, d_{sca} = 0.5 m, F = 400 cm^2

$$K = \frac{0.1}{(10^{-3})\ (10^4)\ (1)}\ (3.29)^2\ \ (0.5)^2\ \ \frac{(400)}{(400)}$$

$$= 0.0131 \rightarrow 1.5 \text{ mm Pb}$$

(2) Secondary leakage, I - 30 mA

$$B = \frac{(0.1)\ (2.29)^2\ (60)\ (30)}{(10^4)\ (1)}$$

$$= 0.094 \rightarrow 3.45 \text{ HVL's} \rightarrow 1.65 \text{ mm Pb}$$

(3) Total secondary 1.65 + 0.48 = 2.13 mm Pb

c. South wall

(1) Secondary scatter, P = 0.01 R/wk, d_{sec} = 10' (3.05 m)

W = 10,000 mA - min/wk, T = 1/4, d_{sca} = 0.5 m,

F = 400 cm^2

$$K = \frac{0.01}{(10^{-3})\ (10^4)\ (1/4)}\ \ (3.05)^2\ (0.5)^2\ \ \frac{(400)}{(400)}$$

$$= 0.0093 \rightarrow 1.7 \text{ mm Pb}$$

(2) Secondary leakage, I = 30 mA

$$B = \frac{(0.1)\ (3.05)^2\ (60)\ (30)}{(10^4)\ (1/4)}$$

$$= 0.067 \rightarrow 3.9 \text{ HVL's} \rightarrow 1.87 \text{ mm Pb}$$

(3) Total secondary 1.87 + 0.48 = 2.35 mm Pb

d. West wall

(1) Secondary scatter, P = 0.01 R/wk, d_{sec} = 7-1/2' (2.29 m)

W = 10,000 mA-min/wk, T = 1/4, d_{sca} = 0.5 m, F = 400 cm^2

$$K = \frac{0.01}{(10^{-3})\ (10^4)\ (1/4)}\ \ (2.29)^2\ (0.5)^2\ \ \frac{(400)}{(400)}$$

$$= 0.00524 \rightarrow 1.95 \text{ mm Pb}$$

(2) Secondary leakage, I = 30 mA

$$B = \frac{(0.01)\ (2.29)^2\ (60)\ (30)}{(10^4)\ \ (1/4)}$$

$$= 0.0376 \rightarrow 4.75 \text{ HVL's} \rightarrow \ 2.28 \text{ mm Pb}$$

(3) Total secondary 2.28 + 0.48 = 2.76 mm Pb

e. Ceiling

(1) Secondary scatter, P = 0.01 R/wk, d_{sec} = 10' (3.05 m)

W = 10,000 mA - min/wk, T = 1/16, d_{sca} = 0.5 m, F=400 cm^2

$$K = \frac{0.01}{(10^{-3})\ (10^{4})\ (1/16)}\ (3.05)^2\ (0.5)^2\ \frac{(400)}{(400)}$$

$$= 0.037 \rightarrow 1.1 \text{ mm Pb}$$

(2) Secondary leakage, I = 30 mA, d_{sec} = 7-1/2' (2.29 m)

$$B = \frac{(0.01)\ (2.29)^2\ (60)\ (30)}{(10^{4})\ (1/16)}$$

$$= 0.0376 \rightarrow 4.75 \text{ HVL's} \rightarrow 2.28 \text{ mm Pb}$$

(3) Total barrier 2.28 + 0.48 = 2.76 mm Pb

3. Summary

Barrier	Total Lead Equivalent - mm	
North wall	3.3	(5/32")*
East wall, door, window	2.13	(3/32")*
South wall	2.35	(3/32")*
West wall	2.76	(1/8")*
Ceiling	2.76	(1/8")*

*Thickness of commercial sheet lead.

LECTURE NO. 14

TITLE:	Radiation Protection Survey
PURPOSE:	To present current recommendations and regulations upon which radiation surveys are based
TIME:	1 hour
VISUAL AIDS:	Blackboard
HANDOUTS:	None
REFERENCES:	NBS Handbook 93
	NCRP Report 33
	NCRP Report 34
	NCRP Report 35
	OSBH Regulations

14. RADIATION PROTECTION SURVEY

I. INTRODUCTION

A radiation protection survey is an evaluation of the radiation levels in and around an installation. It customarily includes a physical survey of the arrangement and use of the equipment and measurements of the exposure rates under expected operating conditions.

All new installations, and existing installations not previously surveyed, are required to have a protection survey made by a person having the knowledge and training necessary to measure ionizing radiations and to advise regarding radiation protection.

II. RADIATION PROTECTION REGULATIONS AND RECOMMENDATIONS

A. X-ray protection is accomplished through the combined efforts of all interested parties

1. Manufacturers of apparatus
2. Designers and builders of x-ray installations
3. Operators of the x-ray equipment

B. To guide, advise, and provide checks on the effectiveness of these individuals, certain guidelines must be established

C. The National Council on Radiation Protection and Measurements (NCRP) has been established to meet this need

III. NCRP

A. Nonprofit corporation chartered by Congress in 1964 to:

1. Collect, analyze, develop and disseminate information and recommendations concerned with radiation protection
2. Provide a means by which organizations may cooperate for effective utilization of their combined resources, and to stimulate the work of such organizations
3. Develop basic concepts about radiation quantities, units and measurements, about the application of these concepts, and about radiation protection
4. Cooperate with all authoritative groups or organizations concerned with radiation protection

B. The Council is the successor to the National Committee on Radiation Protection and Measurements

C. Scientific Committees of the Council

1. Composed of experts having detailed knowledge and competence in a particular area

2. Proposed recommendations are submitted to the full membership of the Council for consideration before being published
3. Recommendations formerly published as NCRP Reports

D. Recommendations of NCRP on medical radiation protection found in NCRP Report Nos. 33 and 34

E. The recommendations of NCRP form the basis for most medical x-ray protection regulations adopted by the Council of State Government and State Radiation Regulatory Agencies

IV. TERMINOLOGY OF RADIATION PROTECTION

A. Terms having specific implications:

1. shall--necessary to meet currently accepted standards of radiation protection
2. should--advisory recommendation to be applied when practicable

B. Terms relating to equipment:

1. Filtration

   a. inherent
   b. added
   c. total

2. Kilovoltage

   a. kVp
   b. kVcp

3. Dead-man type switch
4. Interlock
5. Protective tube housing

   a. diagnostic type
   b. therapeutic type

C. Terms relating to shielding:

1. Controlled area
2. Uncontrolled area
3. Occupancy factor
4. Use factor
5. Workload
6. Protective barriers

   a. primary
   b. secondary

7. Radiation

   a. leakage
   b. scatter
   c. secondary
   d. stray
   e. useful beam

V. GENERAL RECOMMENDATIONS ON SURVEYS

A. Protection Survey

1. New and existing installations
2. Beam restriction and collimation
3. Interlocks
4. Personnel monitoring evaluation
5. Exposure measurements
6. Tube housing leakage

B. Survey Report

1. To person in charge and to person requesting survey
2. Measured exposure levels
3. Recommended corrective measures
4. Recommended resurvey if necessary
5. Copies of report

C. Periodic Inspections

1. Physical inspection of equipment
2. Operating procedures
3. Workloads and occupancy
4. Correct hazards if found

VI. RECOMMENDATIONS ON WORKING CONDITIONS

A. Responsibilities of the user

B. Responsibilities of the operator

C. Responsibilities of the Radiation Protection Officer

D. Personnel monitoring

E. Health records

VII. RECOMMENDATIONS FOR SPECIFIC APPLICATIONS

A. Medical fluoroscopic

1. Equipment
2. Structural shielding
3. Operating procedures

B. Medical radiographic (same as A.)

C. Mobile diagnostic equipment (same as A.)

D. Chest photo fluorographic (same as A.)

E. Dental radiographic (same as A.)

F. Therapeutic up to 3 MeV (same as A.)

G. Therapeutic, 60 kV and below (same as A.)

SECTION II. LABORATORY EXERCISES

GS-462. X-RAY MEASUREMENT

LABORATORY NO. 1

TITLE: X-Ray Output Waveform

PURPOSE: To study x-ray output waveform as a function of kilovoltage, tube current and filtration

TIME: 3 hours

MATERIAL FOR EACH STUDENT GROUP:

One Teaching X-Ray Unit
One solid-state x-ray detector
One Heath Co. 7.5-cm (3 in.) d.c. oscilloscope
One Victoreen model 570 Condenser R-meter with model 70-5, 25 R medium energy chamber
Two sheets linear graph paper, K & E 46-0703 or equivalent

LABORATORY NO. 1

1. X-RAY OUTPUT WAVEFORM

I. INTRODUCTION

The purpose of this laboratory exercise is to investigate the x-ray output waveform from a typical self-rectified x-ray machine, as a function of kilovoltage, tube current, and filtration.

The spectral distribution of the radiation output from an x-ray machine can be measured and/or calculated with reasonable accuracy. The measurement system of choice involves a "large" scintillation crystal and multichannel analyzer system which will sample and present intensity as a function of energy. To calculate spectra requires a precise attenuation curve in aluminum or copper. Measurement systems are expensive and to calculate the spectra is time-consuming unless computer facilities are available.

In this laboratory exercise we will investigate the x-ray output waveform from a typical x-ray machine using an inexpensive solid-state detector and inexpensive oscilloscope. It is important to understand that "x-ray output waveform" is not equivalent to "x-ray output spectrum" in that the solid-state detector indicates intensity as a function of time during the electrical cycle rather than intensity as a function of energy (kilovoltage). The detector used is a typical solar cell. A solid-state amplifier between the detector and readout system increases the detector signal so as to provide adequate signal to the readout system. The readout system is a 7.5-cm (3 in.) d.c. oscilloscope. Using this system the relative x-ray output waveform can be determined at minimum expense.

II. EQUIPMENT AND MATERIAL

A. Teaching X-Ray Unit

B. Solar Cell X-Ray Detector

C. Heath Co. 7.5-cm (3in.) d.c. oscilloscope

D. Linear graph paper

E. R-meter with 25-R chamber

F. Ships curve

III. PROCEDURE

A. Place the amplifier toggle switch on AMPLIFIED

B. Place the detector on the detector mounting stand and place the stand on the bottom of the Teaching X-Ray Unit enclosure in the center of the enclosure

1. Route the detector to amplifier cable through the groove between the left-hand door and the cabinet. Close the enclosure doors.

2. Connect the banana plug terminals on the output cable from the amplifier to the vertical amplifier oscilloscope terminals, red to red, black to black (ground).

3. Position the amplifier and any excess cable such that you have ample working room on the Teaching X-Ray Unit Cart.

4. Connect an insulated lead between the oscilloscope vertical amplifier ground terminal and the x-ray control ground terminal.

5. Turn on the oscilloscope and let it warm up for at least 2 minutes. Set the oscilloscope controls as follows:

   a. Horizontal amplifier DC X1
   b. Vertical amplifier DC X1
   c. Sweep frequency 5
   d. Make any fine adjustments necessary to get an undistorted horizontal trace across the oscilloscope scale with the trace located at the bottom horizontal scale line. This will take some trial and error attempts. If you have difficulty enlist the aid of the instructor, since setting up an oscilloscope requires experience.

C. In each of the following experiments, set up and operate the x-ray machine at the first data point, which will be the maximum exposure rate condition. Make repeated exposures until you have adjusted the oscilloscope settings such that the base line is at the bottom oscilloscope scale, the trace peak is at the top oscilloscope scale and one complete electrical cycle occupies the horizontal oscilloscope scale. Once the oscilloscope scale settings have been established for the first data point, do not change these settings. This also takes experience with oscilloscopes so enlist the aid of your instructor if you have problems.

NOTE: OBSERVE DUTY CYCLE RATINGS FOR ALL EXPOSURES

D. Effect of kilovoltage on x-ray output waveform

1. Set up the x-ray machine as shown below
2. On linear graph paper copy, as accurately as possible, the x-ray output waveform as displayed on the oscilloscope

kVp	mA	Added Filter
100	3.0	0
90	3.0	0
80	3.0	0
70	3.0	0
60	3.0	0
50	3.0	0

E. Effect of tube current on x-ray output waveform

1. Set up the x-ray machine as shown
2. On linear graph paper copy, as accurately as possible, the x-ray output waveform as displayed on the oscilloscope

kVp	mA	Added Filter
70	5	0
70	3	0
70	1	0

F. Effect of filtration on x-ray output waveform

1. Set up the x-ray machine as shown below
2. On linear graph paper copy, as accurately as possible, the x-ray output waveform as displayed on the oscilloscope

kVP	mA	Added Filter
70	3.0	0
70	3.0	1.0 mm Al
70	3.0	2.0 mm Al
70	3.0	3.0 mm Al

G. Using the Victoreen R-meter with 25-R chamber, determine the exposure rate in roentgens per minute at the same x-ray machine settings as used in Part III, Sections D, E, and F for a 35 cm SCD.

IV. QUESTIONS

1. Calculate the area under the waveforms in Parts III, D, E, and F. Does this approximate relative exposure rate determined in Part III. G. in each case? Explain.

2. For each experimental condition (Part III D, III E, III F) explain the change in waveform.

LABORATORY NO. 1

TYPICAL DATA

PART IV. 1. Area under x-ray output waveforms

kVp	Relative Area
100	115
90	100
80	90
70	75
60	55
50	50

mA	Relative Area
5	115
3	75
1	30

Added Filter

mm Al	Relative Area
0	115
1	65
2	40
3	25

Within experimental error the area under the waveforms represents relative exposure rate in that the relative areas follow the measured exposure rates (see data Section III.G.)

2. In all cases, the peak of the waveform decreased with decreasing exposure rate. As kVp is decreased, exposure rate is decreased resulting in a reduced "peak" exposure rate and reduced total area under the waveform. Over the energy range, exposure rate is a linear function of kilovoltage and the area under the waveforms is essentially a linear function of kilovoltage. The same is true of exposure rate and waveform area as a function of tube current. Both exposure rate and waveform area are an exponential function of added filtration.

PART III. G. Exposure rate

Victoreen Condenser R-meter, 25 R chamber, 35 cm SCD

PART III. D. Kilovoltage

kVp	mA	Added filter	Time-min	R	R/min
100	3.0	0	1/2	12.5	25
90	3.0	0	1/2	10.8	21.6
80	3.0	0	1	19	19
70	3.0	0	1	16	16
60	3.0	0	1	13	13
50	3.0	0	1	10	10

PART III. E. Tube current

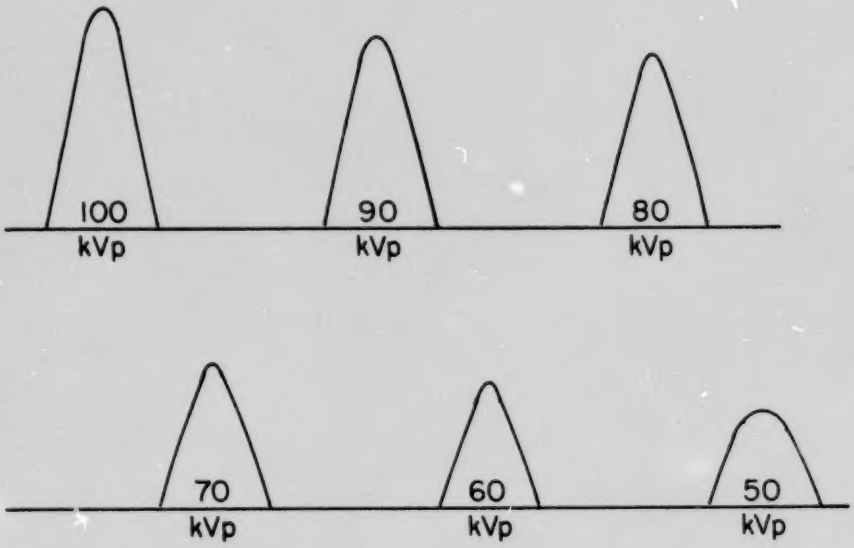
kVp	mA	Added filter	Time-min	R	R/min
70	5	0	1/2	13.3	26.6
70	3	0	1	16	16
70	1	0	2	10.6	5.3

PART III. F. Filtration

kVp	mA	Added filter	Time-min	R	R/min
70	3.0	0	1	16	16
70	3.0	1 mm Al	2	14.4	7.2
70	3.0	2 mm Al	3	13.5	4.5
70	3.0	3 mm Al	4	12.5	3.2

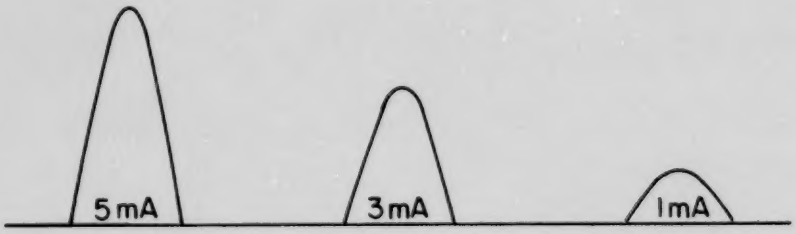
Laboratory No. 1, Section III, Part D2

Effect of Kilovoltage on X-ray Output Waveform.



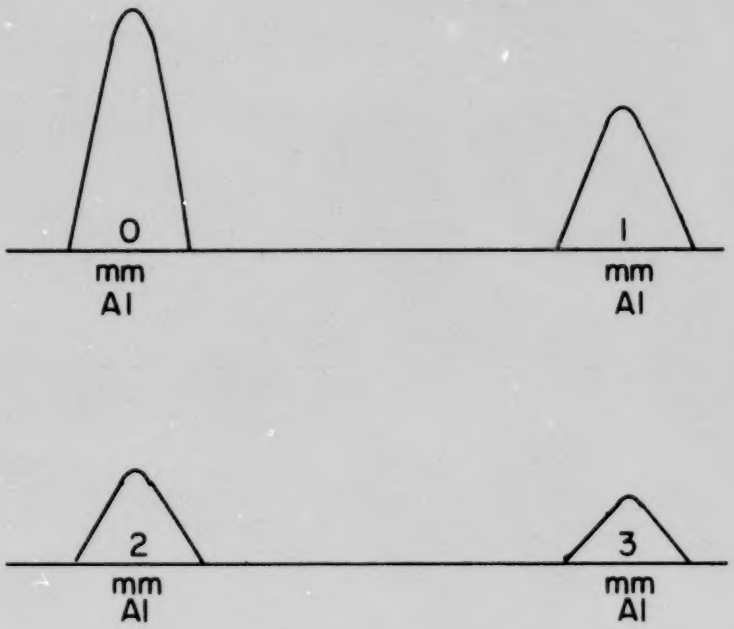
Section III, Part E2

Effect of Tube Current on X-ray Output Waveform



Section III, Part F2

Effect of Filtration on X-ray Output Waveform



LABORATORY NO. 2

TITLE: Factors Affecting Patient and Operator Exposure

PURPOSE: To study the affects of atomic number, kVp, filtration and mA on scattered radiation and patient and operator exposure

TIME: 3 hours

MATERIALS FOR EACH STUDENT GROUP:

One G.E. Maximar 100 X-Ray Machine
One 5 x 30 cm cone
One 10 x 30 cm cone
One 15 x 30 cm cone
One 20 x 30 cm cone
One 3 mm Al filter
One 1 mm Al filter
Two Victoreen Model 555 Radocon II
Two Victoreen Model 555-0.1 MA probes
One 20.3 x 25.4 x 0.05 cm (8 x 10 x 0.020 in.) copper sheet
One 20.3 x 25.4 x 0.32 cm (8 x 10 x 0.125 in.) aluminum sheet
One 20.3 x 25.4 x 1.9 cm (8 x 10 0.750 in.) wood sheet
One 20.3 x 25.4 x 0.04 cm (8 x 10 x 0.015 in.) lead sheet
One wood dowel stand
One 475 cm^3 (16 oz.) water-filled plastic bottle
One chest phantom (3M)
Three sheets linear graph paper, K & E 46-0703 or equivalent
One ships curve, K & E 1685-48 or equivalent
One sheet polar graph paper Dietzgen 340-RP or equivalent

REFERENCES: Evans
The Atomic Nucleus

Hine and Brownell
Radiation Dosimetry

Johns
The Physics of Radiology

LABORATORY NO. 2

2. FACTORS AFFECTING PATIENT AND OPERATOR EXPOSURE

I. INTRODUCTION

The purpose of this laboratory exercise is to study the affects of atomic number, kVp, filtration and mA on scatter radiation and patient and operator exposure.

II. EQUIPMENT

A. General Electric Maximar 100 X-Ray Machine

B. Cones

1. 5 x 30 cm
2. 10 x 30 cm
3. 15 x 30 cm
4. 20 x 30 cm

C. Filters

1. 1 mm Al
2. 3 mm Al

D. Victoreen Radocon II, Model 555 (two required)

E. Victoreen probes, Model 555-0.1 MA (two required)

F. Materials

1. 20.3 x 25.4 x 0.05 cm (8 x 10 x 0.020 in.) copper sheet
2. 20.3 x 25.4 x 0.32 cm (8 x 10 x 0.125 in.) aluminum sheet
3. 20.3 x 25.4 x 1.9 cm (8 x 10 x 0.750 in.) wood sheet
4. 20.3 x 25.4 x 0.04 cm (8 x 10 x 0.015 in.) lead sheet
5. Wood dowel stand
6. H_2O filled plastic bottle
7. Chest phantom

III. X-RAY SCATTER MEASUREMENTS

A. Effect of x-ray energy on Compton scatter

1. Arrange equipment as shown in figure 1 with no attenuator in the primary beam
2. Operate the x-ray machine at 3 mA and 3 mm of Al added filtration and measure the exposure rates at Positions A and B for 50 through 90 kVp in steps of 10 kV
3. Place the aluminum attenuator in the beam and repeat Step 2

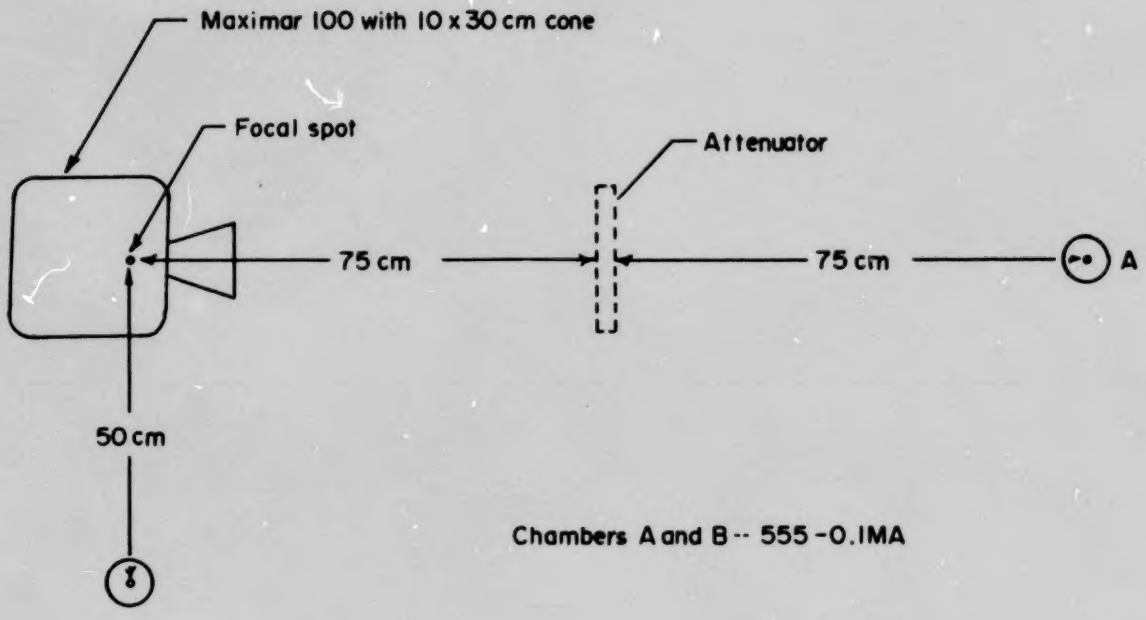


Figure 1

4. Calculate the net scatter exposure rate at Position B*
5. Normalize the net scatter at B to a unit rate of interaction*
6. Plot the normalized net scatter factor versus kVp

B. Effect of atomic number on Compton scatter

1. Arrange equipment as shown in Figure 1
2. Operate the x-ray machine at 90 kVp and 3 mA with 3 mm of Al added filtration. Measure the exposure rates at Positions A and B.
3. Place the aluminum attenuator in the beam and repeat Step 2
4. Repeat Step 3 with copper attenuator
5. Repeat Step 3 with the wood attenuator
6. Repeat Step 3 with the lead attenuator
7. Calculate normalized net scatter factors for each material as in Section III.A
8. Plot scatter factors versus atomic number

C. Distribution of scattered x rays

1. Arrange equipment as shown in figure 2
2. Operate the x-ray machine at 90 kVp and 3 mA with 3 mm of Al added filtration
3. Measure the exposure rate at Positions A through E with and without the cylindrical scattering object in the primary beam
4. Calculate the net exposure rate at each position
5. Plot the exposure rate versus angle of scatter on polar coordinate graph paper. Assume symmetry with respect to the beam axis and draw curve on both sides of the primary beam.

*A description of the procedure for calculating net scatter and normalized net scatter is attached.

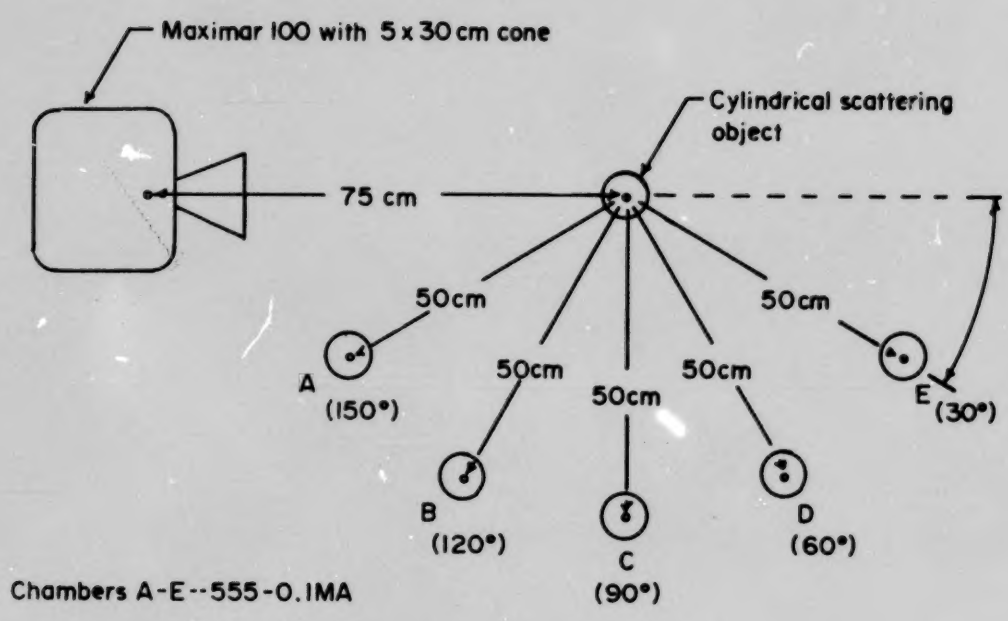


Figure 2

IV. AFFECT OF X-RAY MACHINE FACTORS ON PATIENT AND OPERATOR EXPOSURE

A. kVp and filtration

1. Arrange equipment as shown in figure 3
2. Operate the x-ray machine at 60 kVp and 5 mA with 3 mm of Al added filtration and the 10 x 30 cm cone in place. Measure the exposure rate at Position B.
3. Operate the x-ray machine at 90 kVp with 3 mm of Al added filtration and determine the mA setting which results in the same exposure rate at B as found in Step 2
4. Repeat Step 3 except use 60 kVp and 1 mm of Al added filtration
5. Repeat Step 3 except use 90 kVp and 1 mm of Al added filtration
6. Using the same settings as in Step 5, measure and record the exposure rate at Positions A and C
7. Repeat Step 6 using the settings of Step 4
8. Repeat Step 6 using the settings of Step 3
9. Repeat Step 6 using the settings of Step 2
10. Calculate relative entrance exposure and scatter factors using the 90 kVp, 3 mm Al filtration technique as unity in each case. Report data as follows:

kVp	Added Al filtration	mA	Exit exposure rate	Relative entrance exposure	Relative scatter factor
90	3 mm			1.0	1.0
60	3 mm	5			
90	1 mm				
60	1 mm				

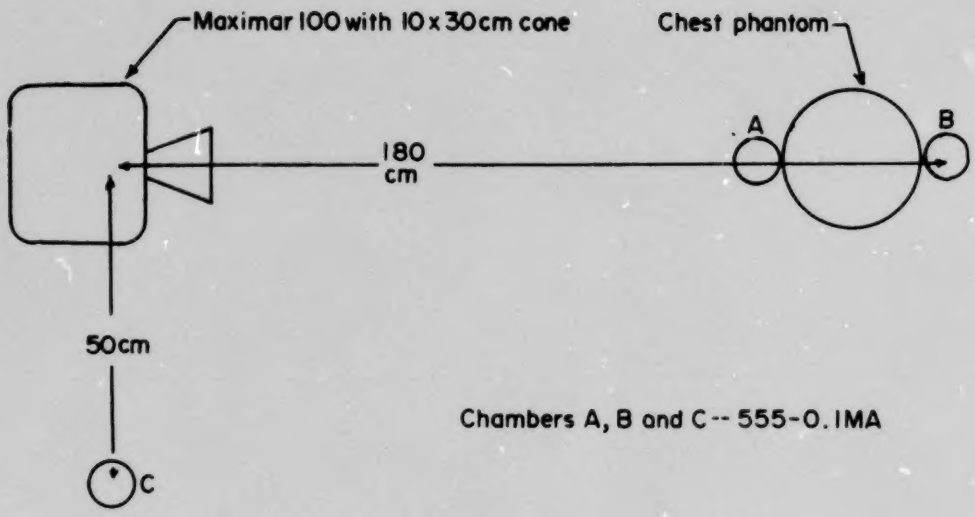


Figure 3

B. Collimation

1. Arrange equipment as shown in figure 3
2. Operate the x-ray machine at 90 kVp and 3 mA with 3 mm of Al added filtration with the 10 x 30 cm cone in place. Measure the scatter at Position C.
3. Replace the cone with the 15 x 30 cm cone and repeat Step 2
4. Replace the cone with the 20 x 30 cm cone and repeat Step 2
5. Calculate the beam diameter at Position B for each cone used
6. Plot beam diameter versus scatter reading. Assume a value for scatter at zero beam diameter and extrapolate curve through this point.

V. QUESTIONS

A. In Part III.A. what is the relation between Compton scatter and kilovoltage? What would the relation be if kilovoltage were to increase above 90 kVp?

B. In Part III.B. what is the relation obtained between atomic number and Compton scatter? Does this agree with theory? Explain.

C. In Part III.C. at what scattering angle is the intensity of the scattered radiation the lowest? Does this agree with theory? Explain.

D. In Part IV.A. which exposure technique produced the lowest patient exposure and which the highest patient exposure? Explain why this occurred.

LABORATORY NO. 2

DETERMINATION OF NET AND NORMALIZED SCATTER

I. NET SCATTER

A. Exposure rate measured with the scatterer (attenuator) in the x-ray beam minus the exposure rate measured without the scatterer (attenuator) in the x-ray beam.

B. Exposure, Part III.A.

1. Assume at 50 kVp chamber reads 0.15 mR/min without the aluminum attenuator in the beam and 0.21 mR/min with the aluminum attenuator in the beam
2. The net scatter would be 0.21 - 0.15 = 0.06 mR/min

II. NORMALIZED SCATTER

A. Net scatter divided by useful beam exposure rate removed by attenuator

B. Example, Part III.A.

1. Same conditions as I.B.
2. Net scatter 0.06 mR/min
3. Useful beam exposure rate removed, chamber A

   a. Exposure rate without attenuator assumed to be 90/mR/min
   b. Exposure rate with attenuator assumed to be 30 mR/min
   c. Exposure rate removed 90 - 30 = 60 mR/min

4. Normalized scatter = 0.06/60 = 0.001

LABORATORY NO. 2

TYPICAL DATA

Part III.A. Effect of x-ray energy on scatter

Attenuator	kVp	mA	R/min "A"-pri	mR/min "B"-sec	mR/min net scatter	Normalized scatter
None	50	3	.098	.1	---	--
"	60	3	.166	.175	---	--
"	70	3	.249	.272	---	--
"	80	3	.322	.372	---	--
"	90	3	.425	.5	---	--
Aluminum	50	3	.028	.18	.08	.00114
"	60	3	.059	.367	.19	.00178
"	70	3	.096	.55	.28	.00183
"	80	3	.141	.77	.40	.00221
"	90	3	.195	1.05	.55	.00239

Part III.B. Effect of atomic number on scatter

Attenuator	kVp	mA	R/min "A"-pri	mR/min "B"-sec	mR/h net scatter	Normalized scatter
Aluminum	90	3	.195	1.05	.55	.00239
Copper	90	3	.056	1.02	.52	.00141
Wood	90	3	.325	2.45	1.95	.0195
Lead	90	3	.00095	1.8	1.3	.00307

Part III.C. Distribution of scatter

Angle	Scatter	Sec-mR/min	Net scatter mR/min
150°	In	3.97	2.24
150°	Out	1.73	
120°	In	2.38	1.8
120°	Out	.58	
90°	In	1.95	1.53
90°	Out	.42	
60°	In	2.6	2.17
60°	Out	.43	
30°	In	3.93	3.18
30°	Out	.75	

Part IV.A. Effect of kVp and filtration on patient and operator exposure

kVp	mA	Filter-mm	R/min "B"-exit	R/min "A"-entrance	mR/min "C"-secondary
60	5	3 Al	0.0145	.41	1.22
90	.85	3 Al	"	.25	.9
60	2.17	1 Al	"	.79	1.6
90	0.60	1 Al	"	.45	1.13

Part IV.B. Effect of field size on operator exposure

Cone-cm	Diameter at Phantom-cm	mR/min
0	0	0
10 x 30	50	2.72
15 x 30	75	4.5
20 x 30	100	5.83

GS-462. LABORATORY NO. 2

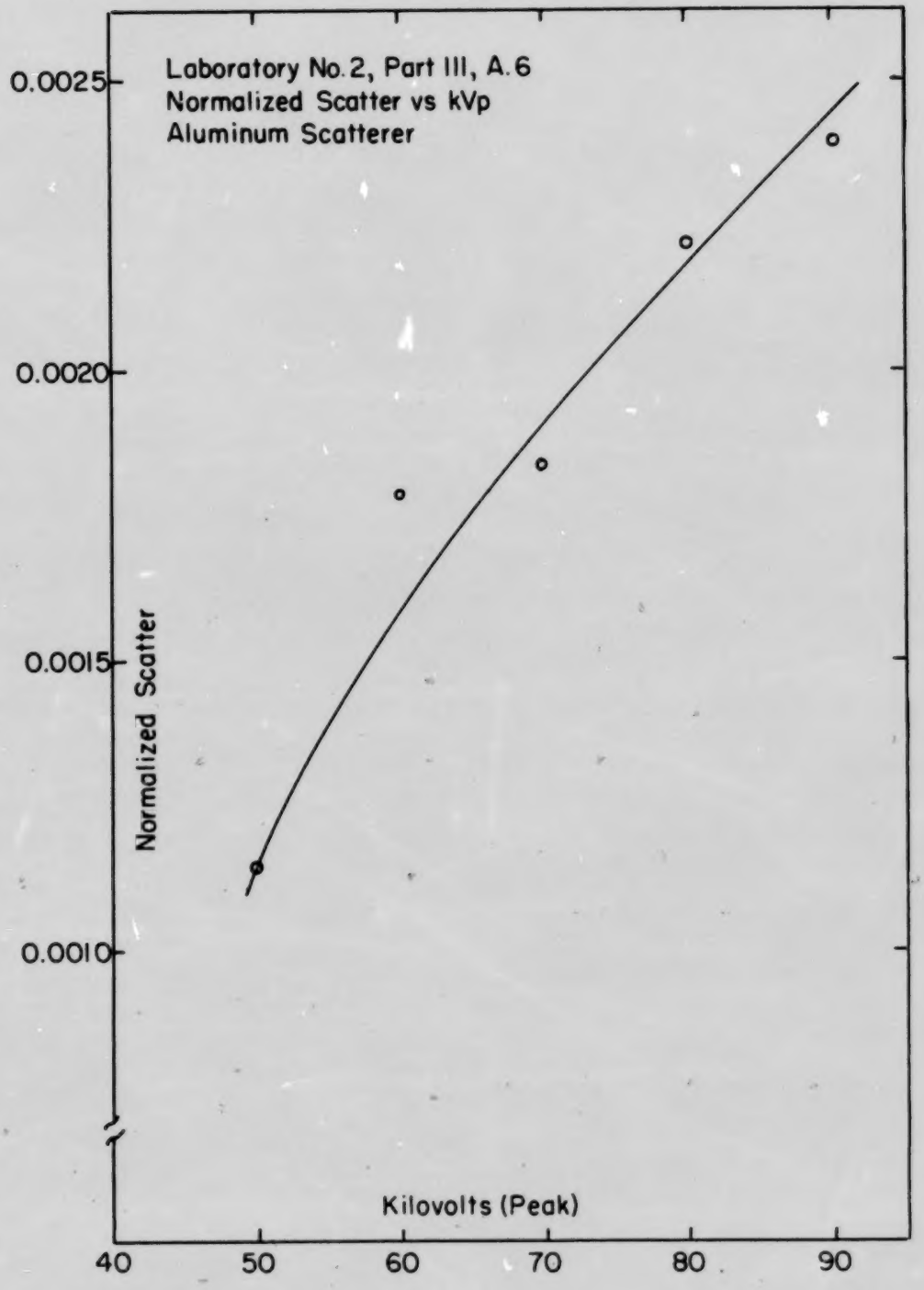
ANSWERS TO QUESTIONS

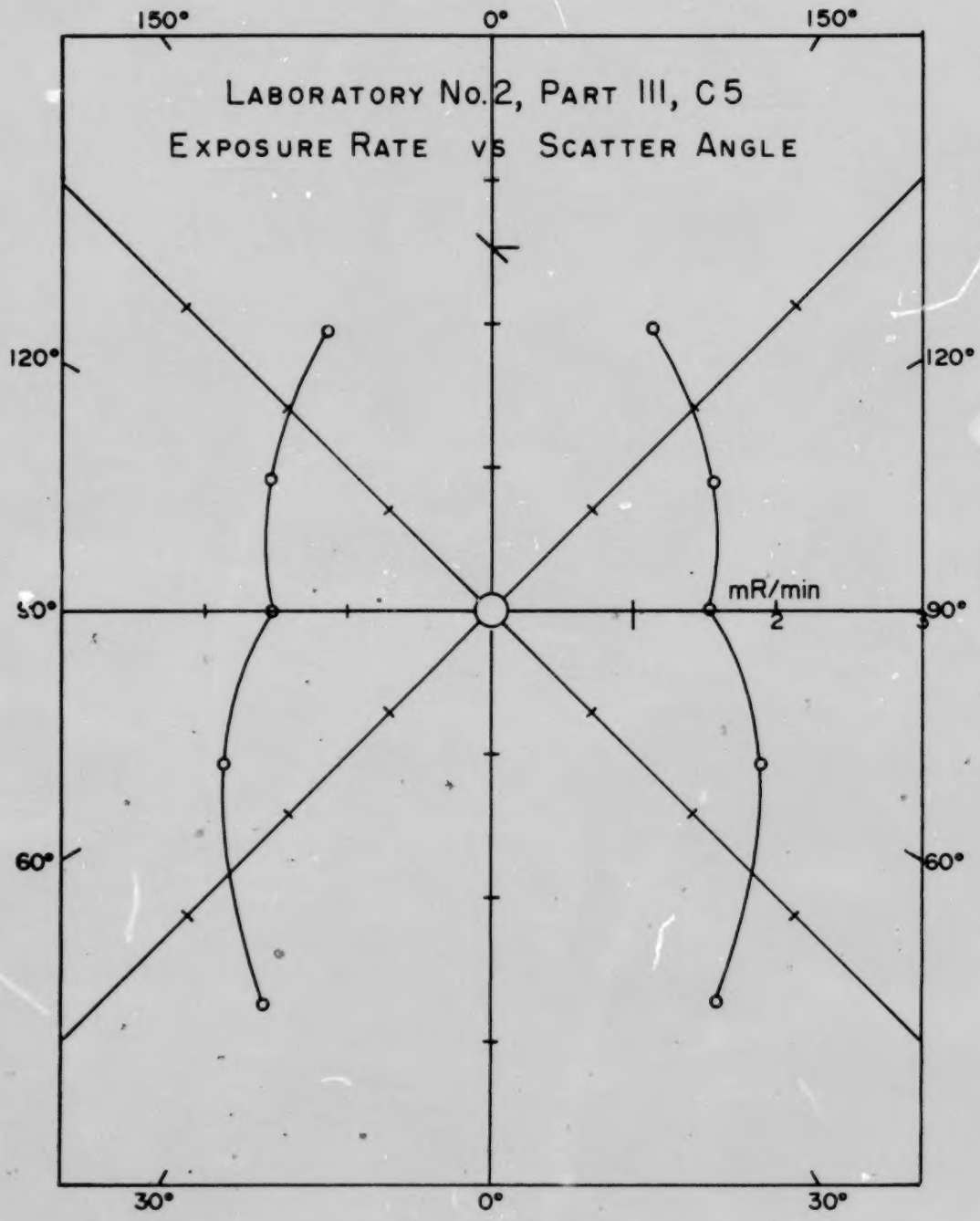
A. Over the kilovoltage range studied, the scatter increases as kilovoltage increases. Since the scatter is from a low atomic number material (aluminum), the scatter will increase to a maximum at approximately 200 kVp and then decrease.

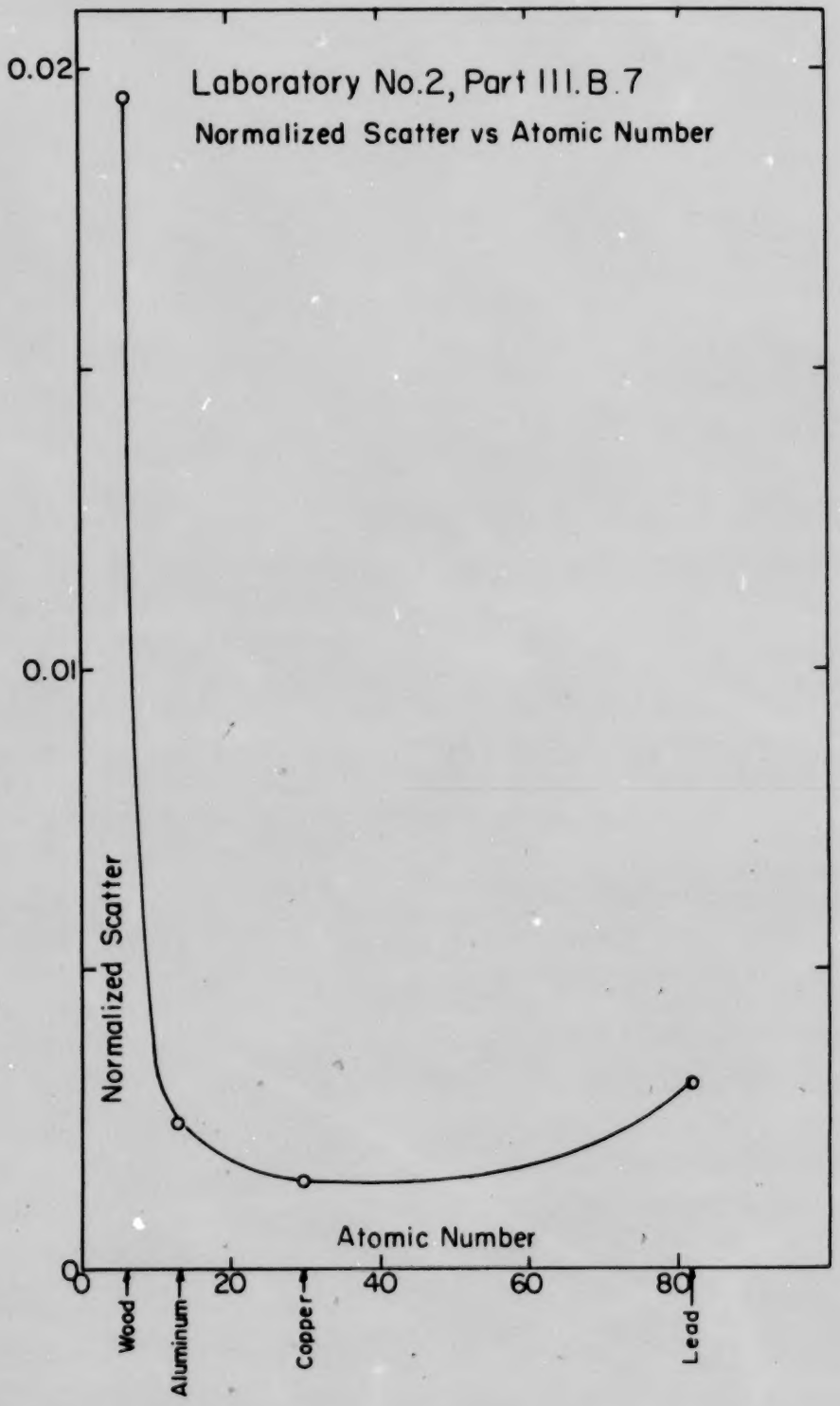
B. Compton's scatter decreases as atomic number increases for a constant rate of interaction in the scattering material, reaching a constant scatter in middle atomic number materials and then increasing for high atomic number materials.

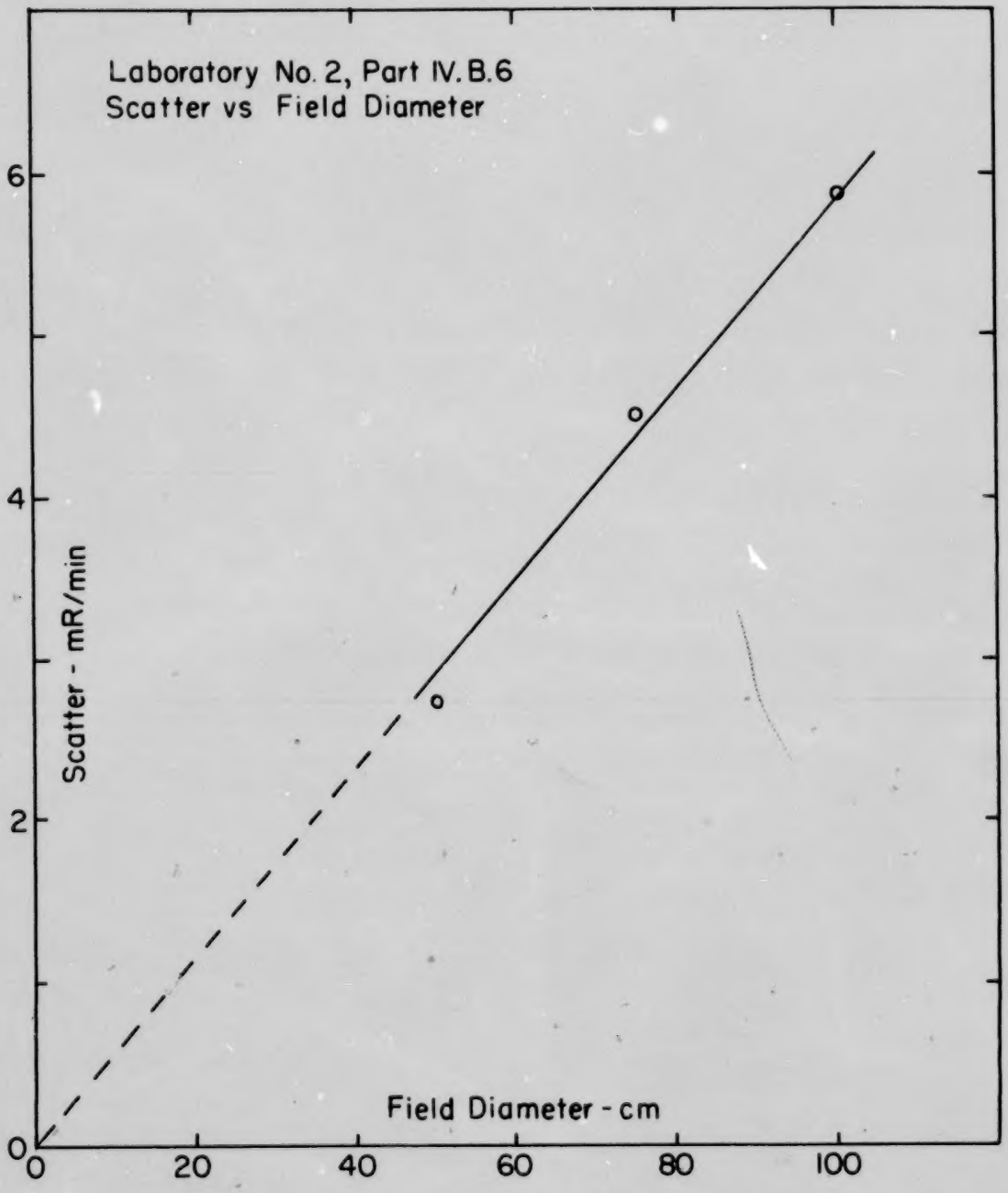
C. The scatter from the unit density cylinder is at a minimum at a scattering angle of approximately 90° to the central x-ray beam, that is at right angles to the central x-ray beam at the axis of the scatterer. For the energy used in this laboratory exercise, the scatter forward in the direction of the x-ray beam, and back, towards the x-ray machine, is in theory approximately twice that scattered at right angles to the x-ray beam.

D. For a constant exit exposure rate, the patient entrance exposure rate is a minimum for the highest voltage, highest filtration technique used, that is 90 kVp with 3 mm Al added filtration. The entrance exposure rate at the higher voltage with lower filtration is approximately the same as that at the lower voltage higher filtration technique, that is 90 kVp, 1 mm Al and 60 kVp, 3 mm Al. The maximum entrance exposure rate occurred with the 60 kilovolt peak, 1 mm Al filtration setting. As kilovoltage is increased, at a constant filtration, the x-ray beam will nave an increasing proportion of higher energy x-ray photons which will pass through the patient without interaction to reach the exit surface or the x-ray film. As a result, the entrance exposure will decrease for a given exit exposure as kilovoltage is increased. At a constant kilovoltage, increasing filtration will remove from the beam the lower energy photons which would be absorbed in the patient and not reach the exit surface and, therefore, the entrance exposure for a given exit exposure will also decrease. From this, one would conclude that the highest voltage highest filtration technique would provide the lowest patient exposure for a given exit exposure or exposure to the film. This is correct, but other factors which influence the radiographic image, as we will discuss next term, may require a lower voltage or a lower filtration technique.


Laboratory No. 2, Part III, A.6
Normalized Scatter vs kVp
Aluminum Scatterer
0.0025
0.0020
0.0015
0.0010
Normalized Scatter
Kilovolts (Peak)
40
50
60
70
80
90


LABORATORY No. 2, PART III, C5
EXPOSURE RATE VS SCATTER ANGLE
150°
0°
150°
120°
120°
90°
90°
60°
60°
30°
0°
30°
mR/min
1
2
3


Laboratory No.2, Part III.B.7
Normalized Scatter vs Atomic Number
0.02
0.01
0
Normalized Scatter
Atomic Number
0
20
40
60
80
Wood
Aluminum
Copper
Lead


Laboratory No. 2, Part IV. B.6
Scatter vs Field Diameter
Scatter - mR/min
Field Diameter - cm
0
2
4
6
0
20
40
60
80
100

LABORATORY NO. 3

TITLE: Determination of X-Ray Field Distribution

PURPOSE: To study the x-ray field distribution from an x-ray machine

TIME: 3 hours

MATERIALS FOR EACH STUDENT GROUP:

One Teaching X-Ray Unit
One Condenser R-meter with 25 R medium energy chamber
Two sheets linear graph paper, K & E 46-0703 or equivalent
One ships curve, K & E 1685-48 or equivalent

REFERENCES: Atlee, Z. J. and E. D. Trout
"A Study of Roentgen-Ray Distribution at 60-140 kVp" Radiology, 40 (4), pp. 375-385, April 1943

LABORATORY NO. 3

3. DETERMINATION OF X-RAY FIELD DISTRIBUTION

I. INTRODUCTION

The purpose of this laboratory exercise is to study the x-ray field distribution from an x-ray machine.

II. EQUIPMENT

A. Teaching X-Ray Unit

B. Condenser R-meter with 25 R medium energy chamber

III. PROCEDURE

A. Determination of x-ray field distribution

1. Under the following conditions using an open field (not diaphragmed) measure the exposure at the center of the field using an exposure time of 45 seconds. Then at 2.5 cm intervals measure the exposure along the tube axis. Convert the exposures to percentages with that on the beam axis (center of the field) as 100 percent.

kVp	mA	SCD	Filter	Position	R	Percent
70	3	35 cm	Inherent	Center		100
70	3	35 cm	Inherent	2.5 cm right		
70	3	35 cm	Inherent	5 cm right		
70	3	35 cm	Inherent	7.5 cm right		
70	3	35 cm	Inherent	10 cm right		
70	3	35 cm	Inherent	2.5 cm left		
70	3	35 cm	Inherent	5 cm left		
70	3	35 cm	Inherent	7.5 cm left		
70	3	35 cm	Inherent	10 cm left		

2. Repeat, measuring the exposure at 2.5 cm intervals perpendicular to the tube axis

kVp	mA	SCD	Filter	Position	R	Percent
70	3	35 cm	Inherent	Center		100
70	3	35 cm	Inherent	2.5 cm back		
70	3	35 cm	Inherent	5 cm back		
70	3	35 cm	Inherent	7.5 cm back		
70	3	35 cm	Innerent	10 cm back		
70	3	35 cm	Inherent	2.5 cm front		
70	3	35 cm	Inherent	5 cm front		
70	3	35 cm	Inherent	7.5 cm front		
70	3	35 cm	Innerent	10 cm front		

3. On separate sheets of linear graph paper, plot exposure percentage versus distance from field center for Parts III. A. 1 and 2

4. Repeat Part III.A.1. with 2 mm Al added filtration and an exposure time of 2-1/2 minutes

kVp	mA	SCD	Filter	Position	R	Percent
70	3	35 cm	2 mm Al	Center		100
70	3	35 cm	2 mm Al	2.5 cm right		
70	3	35 cm	2 mm Al	5 cm right		
70	3	35 cm	2 mm Al	7.5 cm right		
70	3	35 cm	2 mm Al	10 cm right		
70	3	35 cm	2 mm Al	2.5 cm left		
70	3	35 cm	2 mm Al	5 cm left		
70	3	35 cm	2 mm Al	7.5 cm left		
70	3	35 cm	2 mm Al	10 cm left		

5. Repeat Part III.A.2. with 2 mm Al added filtration and an exposure time of 2-1/2 minutes

kVp	mA	SCD	Filter	Position	R	Percent
70	3	35 cm	2 mm Al	Center		100
70	3	35 cm	2 mm Al	2.5 cm back		
70	3	35 cm	2 mm Al	5 cm back		
70	3	35 cm	2 mm Al	7.5 cm back		
70	3	35 cm	2 mm Al	10 cm back		
70	3	35 cm	2 mm Al	2.5 cm front		
70	3	35 cm	2 mm Al	5 cm front		
70	3	35 cm	2 mm Al	7.5 cm front		
70	3	35 cm	2 mm Al	10 cm front		

6. On the two sheets of graph paper used in Part III.A. 1 and 2, plot exposure percentage versus distance from field center for Parts III.A. 4 and 5

IV. QUESTIONS

A. What is the "heel" effect: how does it alter the x-ray field distribution?

B. Given a SCD of 50 cm and a field diameter of 36 cm, evaluate the reduction in intensity at the edges of the field due only to the inverse square law.

C. Which position, left or right of field center, is in the direction of the tube anode? Explain your answer.

D. What is the effect of added filtration on field distribution parallel and perpendicular to the x-ray tube axis. Explain the effect, if any, observed.

LABORATORY NO. 3

TYPICAL DATA

Part III.A. X-ray field distribution

1. Parallel to x-ray tube axis, no added filter

Position	R	Percent
Axis	15.4	100
2.5 cm right	12.6	82
5 cm right	9.1	59
7.5 cm right	2.6	17
10 cm right	0.3	2
2.5 cm left	16.8	109
5 cm left	18.1	118
7.5 cm left	7.8	50.5
10 cm left	0.1	0.5

2. Perpendicular to x-ray tube axis, no added filter

Position	R	Percent
Axis	15.4	100
2.5 cm back	15.4	100
5 cm back	15.2	99
7.5 cm back	14.4	93.5
10 cm back	0.2	1.5
2.5 cm front	15.4	100
5 cm front	15.2	99
7.5 cm front	14.5	94
10 cm front	0.3	2

3. Parallel to x-ray tube axis, 2 mm Al added filter

Position	R	Percent
Axis	14.4	100
2.5 cm right	13.1	91
5 cm right	10.9	75.5
7.5 cm right	3.3	23
10 cm right	0.3	2
2.5 cm left	15.2	106
5 cm left	14.9	103
7.5 cm left	6.5	45
10 cm left	0.3	2

5. Perpendicular to x-ray tube axis, 2 mm Al added filter

Position	R	Percent
Axis	14.4	100
2.5 cm back	14.4	100
5 cm back	14.1	98
7.5 cm back	13.0	90
10 cm back	0.3	2
2.5 cm front	14.4	100
5 cm front	14.0	97
7.5 cm front	12.8	89
10 cm front	0.3	2

Part IV. ANSWERS TO QUESTIONS

A. The "heel" effect is the name given to the effect produced by attenuation of x rays within the target. The "heel" effect occurs because not all x rays are produced at the outermost surface of the target. The electrons penetrate the surface of the target and x rays are produced at a depth within the target. The x rays produced within the target are filtered by the tungsten of the target resulting in loss in intensity. The amount of tungsten that must be penetrated increases toward the "heel" of the target (the anode end of the x-ray tube) because of the target angle.

B. Distance to edge of field (D) from focal spot is:

$$D^2 = (SCD)^2 + \left(\frac{\text{Field Diameter}}{2}\right)^2$$

$$= (50)^2 + \left(\frac{36}{2}\right)^2 = 2824$$

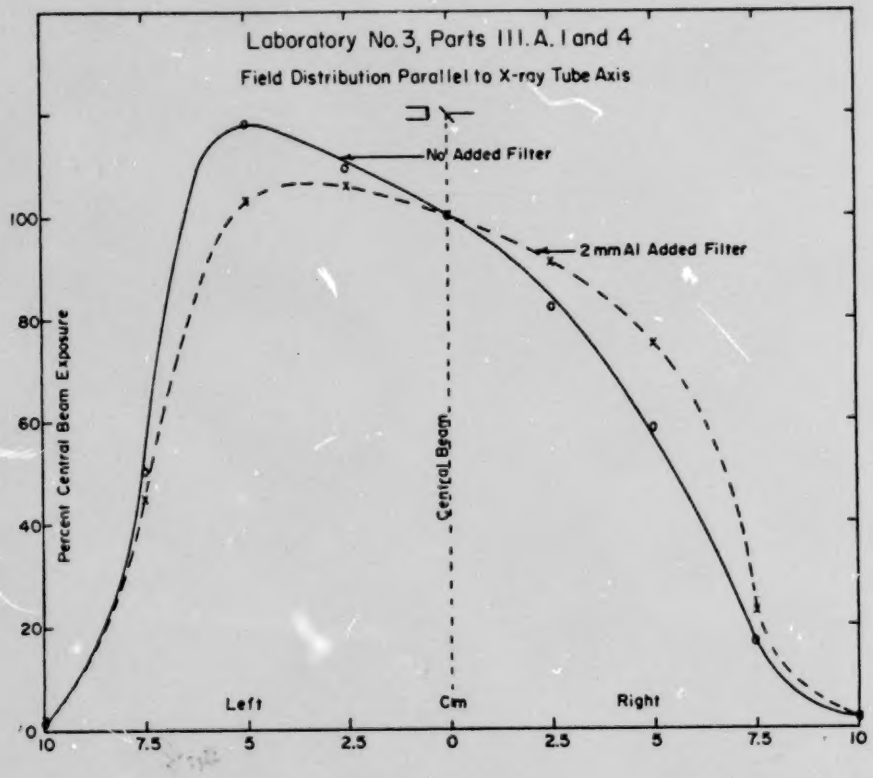
$$\frac{SCD}{D^2} = \frac{(50)^2}{2824} = 0.885$$

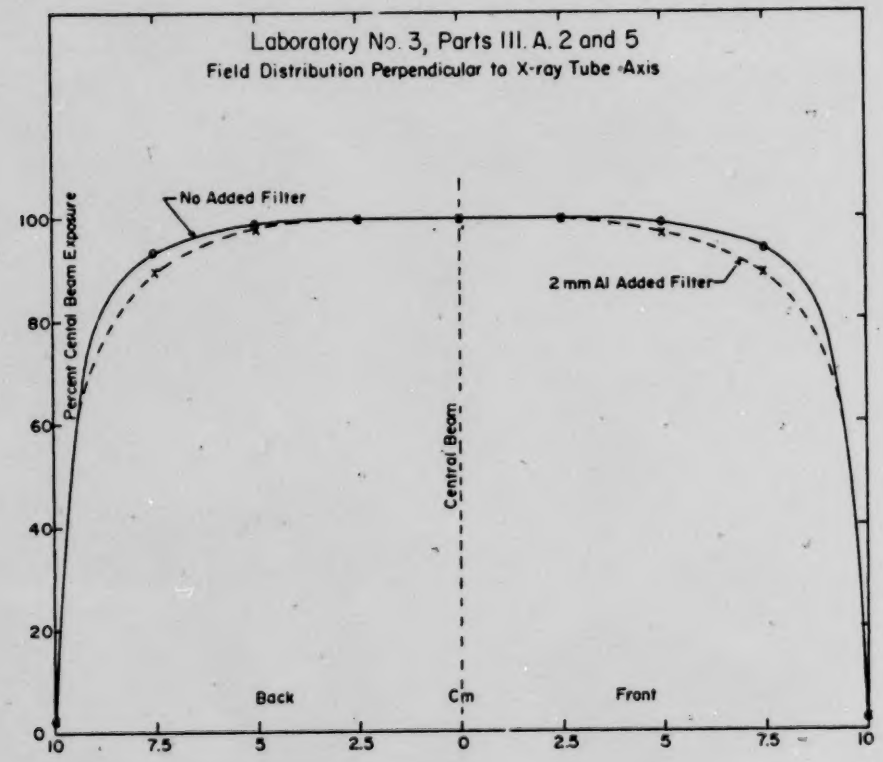
Therefore, intensity at field edge is reduced 1.000 - 0.885 = 0.115 or 11.5 percent.

C. The direction of the anode is toward the right. This is apparent from the reduced field distribution resulting from attenuation of x-ray photons in the target on the right of field center.

D. The effect of added filtration parallel to the x-ray tube axis is to "flatten" the field and shift the distribution toward the anode. The effective thickness of the plane (flat) filter increases as the distance from the field center increases. The average or effective energy of x-ray photons on the anode side of field center is greater than those on the cathode side because of the "heel" effect: i.e., filtration in the target. As a result, the added filter will reduce the exposure rate, percentage-wise, more on the cathode side of field center than on the anode side resulting in the effect observed.

Perpendicular to the x-ray tube axis the added filtration tends to narrow the field because of the increasing effective filter thickness as the distance from the field center increases.


Laboratory No. 3, Parts III. A. 1 and 4
Field Distribution Parallel to X-ray Tube Axis
No Added Filter
2 mm Al Added Filter
Percent Central Beam Exposure
Central Beam
Left
Cm
Right
100
80
60
40
20
0
10
7.5
5
2.5
0
2.5
5
7.5
10


Laboratory No. 3, Parts III. A. 2 and 5
Field Distribution Perpendicular to X-ray Tube Axis
No Added Filter
2 mm Al Added Filter
Percent Central Beam Exposure
Central Beam
Back
Cm
Front
100
80
60
40
20
0
10
7.5
5
2.5
0
2.5
5
7.5
10

LABORATORY NO. 4

TITLE: Determination of Half-Value Layer

PURPOSE: To determine the first half-value layer, second half-value layer and the homogeneity coefficient for both "broad beam" and "unique" conditions of geometry

TIME; 3 hours

EQUIPMENT FOR EACH STUDENT GROUP:

One Teaching X-Ray Unit
One Victoreen R-meter with 25 R chamber
One chamber holder
One 0.25 mm aluminum filter (absorber)
One 0.5 mm aluminum filter (absorber)
Three 1.0 mm aluminum filters (absorbers)
One 1.0 cm diameter lead diaphragm
One 4.0 cm diameter lead diaphragm

REFERENCES:

Trout, E. D., J. P. Kelley and A. C. Lucas, Determination of Half-Value Layer, American Journal of Roentgenology, Radium Therapy and Nuclear Medicine, Vol. 84, No. 4, 729-740, October 1960

Trout, E. D., J. P. Kelley and A. C. Lucas, The Second Half-Value Layer and the Homogeneity Coefficient, American Journal of Roentgenology, Radium Therapy and Nuclear Medicine, Vol. 87, No. 3, 574-584, March 1962

Three sheets of linear graph paper, K & E 46-0703 or equivalent
Two sheets of 2-cycle semi-log paper, K & E 46-5253 or equivalent
One straight edge
One ships curve, K & E 1685-48 or equivalent

LABORATORY NO. 4

4. DETERMINATION OF HALF-VALUE LAYER

OBJECT

To make exposure rate measurements through increasing thicknesses of aluminum at two kilovoltages and with two field sizes, to plot these data as absorption curves, from the curves determine the first and second half-value layers and the homogeneity factor, and from these data determine the "unique" first and second half-value layers and homogeneity factor.

PROCEDURE

PART I. ALUMINUM FILTERS

A. Using a metric micrometer, measure and record the thickness of each of the aluminum absorbers

B. Use the measured absorber thickness in plotting your data

PART II. DETERMINATION OF HALF-VALUE LAYER, 50 kVp

A. Determine the exposure rate in R/minute with no added absorber, 1/4 mm Al, 1/2 mm Al, 1 mm Al, and 2 mm Al added absorber, operating the x-ray unit at 50 kVp, 3.0 mA with a 25 cm SCD and using the 4 cm diameter lead diaphragm

B. On a sheet of semi-log paper, plot exposure rate versus added absorber thickness

C. From the absorption curve determine the first half-value layer, the second half-value layer and the homogeneity factor

D. Repeat Part II. A. using a 1.0 cm diameter diaphragm

E. On a second sheet of semi-log paper, plot the exposure rate versus added absorber thickness

F. From the absorption curve determine the first half-value layer, second half-value layer and the homogeneity factor.

PART III. DETERMINATION OF HALF-VALUE LAYER, 100 kVp

A. Determine the exposure rate in R/minute with no added absorber, 1/4 mm Al, 1/2 mm Al, 1 mm Al, 2 mm Al, 3 mm Al, and 3-1/2 mm Al added absorber operating the x-ray unit at 100 kVp, 3.0 mA with a 25 mm SCD and using the 1 cm diameter lead diaphragm

B. On the same sheet of semi-log paper used in Part II. E., plot exposure rate versus added absorber thickness

C. From the absorption curve, determine the first half-value layer, the second half-value layer and the homogeneity factor

D. Repeat Part III.A. using the 4.0 cm diameter diaphragm

E. On the same sheet of semi-log paper used in Part II.B., plot exposure rate versus added absorber thickness

F. From the absorption curve, determine the first half-value layer, second half-value layer and the homogeneity factor

PART IV. DETERMINATION OF "UNIQUE" 1 HVL, 2 HVL BY EXTRAPOLATION TO ZERO FIELD DIAMETER AND THE "UNIQUE" HOMOGENEITY FACTOR

A. On a sheet of cross section paper, plot the first half-value layer versus field diameter for Part II.C. and Part II.F. and extrapolate to zero field diameter. The half-value layer at zero field is the "unique" half-value layer. Repeat for the second half-value layer. Determine the "unique" homogeneity factor.

B. On a second sheet of cross section paper plot the first half-value layer versus field diameter for Part III.C. and Part III.F. and extrapolate to zero field diameter. Repeat for the second half-value layer. Determine the "unique" homogeneity factor.

PART V. DETERMINATION OF "UNIQUE" 1 HVL AND 2 HVL BY CALCULATION METHOD AND THE "UNIQUE" HOMOGENEITY COEFFICIENT

A. The "unique" half-value layer can be calculated from the half-value layer determined under "broad beam" conditions if the geometry used in making the determination is known. This procedure is discussed in the first reference listed in this laboratory exercise. The geometric variables are:

1. field diameter at the added absorbers (correction K_1),
2. focal-absorber distance (correction K_2), and
3. focal-chamber distance (correction K_3).

B. The half-value layer determined by adding absorbers to the beam, H, is related to the "unique" half-value layer, H_o, by:

$$H_o = \frac{H}{1 + K_1 K_2 K_3}$$

C. Calculate the "unique" half-value layers, both 1 HVL and 2 HVL, for the half-value layers determined at 100 kVp, 4 cm diameter diaphragm given the following information:

1. diameter of beam at added absorbers = 4.0 cm

   a. correction K_1 for 1 HVL = 0.018*
   b. correction K_1 for 2 HVL = 0.021*

2. focal-absorber distance 9 cm, correction K_2 = 1.03*
3. focal-chamber distance 25 cm, correction K_3 = 2.3*

*Determined from data in references listed for this laboratory exercise.

PART VI. QUESTIONS

A. Define first and second half-value layer and homogeneity factor.

B. Discuss the variation of first and second half-value layer with field size at the filter.

C. Which half-value layer, first or second, is the greater for a given x-ray beam and why?

D. Explain why the homogeneity factor is never greater than unity.

E. Given the following data and your data on "unique" first half-value layers (Part IV), determine the effective energy of your 50 kVp and 100 kVp beams. Assume the density of aluminum to be 2.70 g/cm^3.

Effective Energy and Mass Attentuation Coefficient

keV	μ/ρ - cm^2/g
10	26.2
15	7.9
20	3.37
30	1.11
40	0.543
50	0.353
60	0.268
80	0.197
100	0.169

Name _____

Date _____

Unit _____

Temperature _____

Pressure _____

Correction Factor _____

TEACHING X-RAY UNIT

Laboratory No. 4 Determination of half-value layer.

Part I, Section A. Measured aluminum absorber thickness.

Nominal mm Al	Measured mm Al
1/4	_____
1/2	_____
1	_____
1	_____
1	_____

Part II, Section A. Absorption in aluminum: 50 kVp, 3 mA, 25 cm SCD, 4 cm diameter diaphragm.

Added Absorber	Exposure Time	Uncorrected Exposure	Corrected Exposure	Exposure Rate
None	30 sec	_____ R	_____ R	_____ R/m
1/4 mm Al	60 sec	_____ R	_____ R	_____ R/m
1/2 mm Al	60 sec	_____ R	_____ R	_____ R/m
1 mm Al	90 sec	_____ R	_____ R	_____ R/m
2 mm Al	150 sec	_____ R	_____ R	_____ R/m

Part II, Section C. First half-value layer, second half-value layer and homogeneity factor: 50 kVp, 4 cm diameter diaphragm.

1 HVL - mm Al	2 HVL - mm Al	Homogeneity Factor
_____	_____	_____

Part II, Section D. Absorption in aluminum: 50 kVp, 3 mA, 25 cm SCD, 1 cm diameter diaphragm.

Added Absorber	Exposure Time	Uncorrected Exposure	Corrected Exposure	Exposure Rate
None	30 sec	_____ R	_____ R	_____ R/m
1/4 mm Al	60 sec	_____ R	_____ R	_____ R/m
1/2 mm Al	60 sec	_____ R	_____ R	_____ R/m
1 mm Al	90 sec	_____ R	_____ R	_____ R/m
2 mm Al	150 sec	_____ R	_____ R	_____ R/m

Part II, Section F. First half-value layer, second half-value layer and homogeneity factor: 50 kVp, 1 cm diameter diaphragm.

1 HVL - mm Al	2 HVL - mm Al	Homogeneity Factor
_____	_____	_____

Part III, Section A. Absorption in aluminum: 100 kVp, 3 mA, 25 cm SCD, 1 cm diameter diaphragm.

Added Absorber	Exposure Time	Uncorrected Exposure	Corrected Exposure	Exposure Rate
None	15 sec	_____ R	_____ R	_____ R/m
1/4 mm Al	15 sec	_____ R	_____ R	_____ R/m
1/2 mm Al	20 sec	_____ R	_____ R	_____ R/m
1 mm Al	30 sec	_____ R	_____ R	_____ R/m
2 mm Al	30 sec	_____ R	_____ R	_____ R/m
3 mm Al	40 sec	_____ R	_____ R	_____ R/m
3-1/2 mm Al	50 sec	_____ R	_____ R	_____ R/m

Part III, Section C. First half-value layer, second half-value layer and homogeneity factor: 100 kVp, 1 cm diameter diaphragm.

1 HVL - mm Al	2 HVL - mm Al	Homogeneity Factor
_____	_____	_____

Part III, Section D. Absorption in aluminum: 100 kVp, 3 mA, 25 cm SCD, 4 cm diameter diaphragm.

Added Absorber	Exposure Time	Uncorrected Exposure	Corrected Exposure	Exposure Rate
None	15 sec	_____R	_____R	_____R/m
1/4 mm Al	15 sec	_____R	_____R	_____R/m
1/2 mm Al	20 sec	_____R	_____R	_____R/m
1 mm Al	30 sec	_____R	_____R	_____R/m
2 mm Al	30 sec	_____R	_____R	_____R/m
3 mm Al	40 sec	_____R	_____R	_____R/m
3-1/2 mm Al	50 sec	_____R	_____R	_____R/m

Part III, Section F. First half-value layer, second half-value layer and homogeneity factor: 100 kVp, 4 cm diameter diaphragm.

1 HVL - mm Al	2 HVL - mm Al	Homogeneity Factor
_____	_____	_____

Part IV, Section A. "Unique" first half-value layer, second half-value layer and homogeneity factor: 50 kVp.

"Unique" 1 HVL - mm Al	"Unique" 2 HVL - mm Al	"Unique" Homogeneity Factor
_____	_____	_____

Part IV, Section B. "Unique" first half-value layer, second half-value layer and homogeneity factor: 100 kVp.

"Unique" 1 HVL - mm Al	"Unique" 2 HVL - mm Al	"Unique" Homogeneity Factor
_____	_____	_____

LABORATORY NO. 4

TYPICAL DATA

Section I.A.

Nominal mm Al	Measured mm Al
1/4	0.26
1/2	0.51
1	1.01
1	0.99
1	1.00

Section II.A. 50 kVp, 3 mA, 25 cm SCD, 4.0 cm diameter diaphragm

Added Absorber

mm Al	R/min
0	25.8
1/4	16.2
1/2	12.9
1	8.7
1	4.9

Section II.D. 50 kVp, 3 mA, 25 cm SCD, 1.0 cm diameter diaphragm

Added Absorber

mm Al	R/min
0	24.6
1/4	15.6
1/2	12.0
1	8.3
2	4.6

Section III.A. 100 kVp, 3 mA, 25 cm SCD, 1.0 cm diameter diaphragm

Added Absorber

mm Al	R/min
0	60.4
1/4	46.0
1/2	39.9
1	31.4
2	22.0
3	16.9
3-1/2	14.9

Section III.D 100 kVp, 3 mA, 25 cm SCD, 4.0 cm diameter diaphragm

Added Absorber

mm Al	R/min
0	62.8
1/4	46.8
1/2	41.4
1	32.8
2	23.0
3	17.3
3-1/2	15.4

Section II.F. 1 HVL, 2 HVL and H, 50 kVp

Diaphragm Diameter - cm	1 HVL	2 HVL	H
1.0	0.48 mm Al	0.99 mm Al	0.49
4.0	0.50 mm Al	1.00 mm Al	0.50

Section III.F. 1 HVL, 2 HVL and H, 100 kVp

Diaphragm Diameter - cm	1 HVL	2 HVL	H
1.0	1.07 mm Al	2.32 mm Al	0.46
4.0	1.09 mm Al	2.35 mm Al	0.47

Section IV.A. "Unique" 1 HVL, 2 HVL and H_o, 50 kVp

	Unique
1 HVL	0.47 mm Al
2 HVL	0.98 mm Al
H_o	0.48

Section IV. B. "Unique" 1 HVL, 2 HVL and H_o, 100 kVp

	Unique
1 HVL	1.06 mm Al
2 HVL	2.29 mm Al
H_o	0.46

Section V.C. Calculation of "unique" 1 HVL, 2 HVL and H_o, 100 kVp, 4.0 cm diameter diaphragm.

$$1\ HVL_o = 1.09/1 + (0.018)(1.03)(2.3) = 1.05 \text{ mm Al}$$

$$2\ HVL_o = 2.35/1 + (0.021)(1.03)(2.3) = 2.25 \text{ mm Al}$$

IV. ANSWERS TO QUESTIONS

A. The half-value layer is defined as the thickness of a specified material necessary to reduce the intensity of an x-ray or γ-ray beam to one-half its original value.

The first half-value layer reduces the intensity of a beam of x rays from 100 percent to 50 percent. The second half-value layer reduces the intensity of a beam of x rays from 50 percent to 25 percent.

B. The first and second HVL decrease with decreasing field size at the filter. The decrease in HVL has been found to be a linear function of a field diameter at the filter and is the result of the decreasing amounts of scattered radiation into the detector field as size decreases.

C. For a monoenergetic x-ray beam the first and second HVL's are identcal because the addition of one HVL to the beam does not alter the energy spectrum of the beam.

For a heterogenous x-ray beam the first HVL is smaller than the second HVL. This condition is a direct result of the shift in the energy spectrum of the x-ray beam that occurs upon the insertion of one HVL into the beam. The effective energy of the beam after the insertion of one HVL is greater than before; thus it will take a greater thickness of absorber to reduce the beam by 50 percent, therefore, the second HVL must be larger than the first HVL.

D. The homogeneity coefficient is defined as the ratio of the first HVL to the second HVL; (1st HVL/2nd HVL). For a monoenergetic x-ray beam the homogeneity coefficient will be unity because the first and second HVL's are identical. For a heterogenous x-ray beam the homogeneity coefficient will always be less than unity because the second HVL is always larger than the first HVL. The answers to question C explain why the second HVL is larger than the first HVL.

E. $HVL = 0.693/\mu$

$\mu = 0.693/HVL$

From Lab data: HVL at 50 kVp = 0.47 mm Al
HVL at 100 kVp = 1.06 mm Al
ρ for aluminum = 2.7 g/cm^3

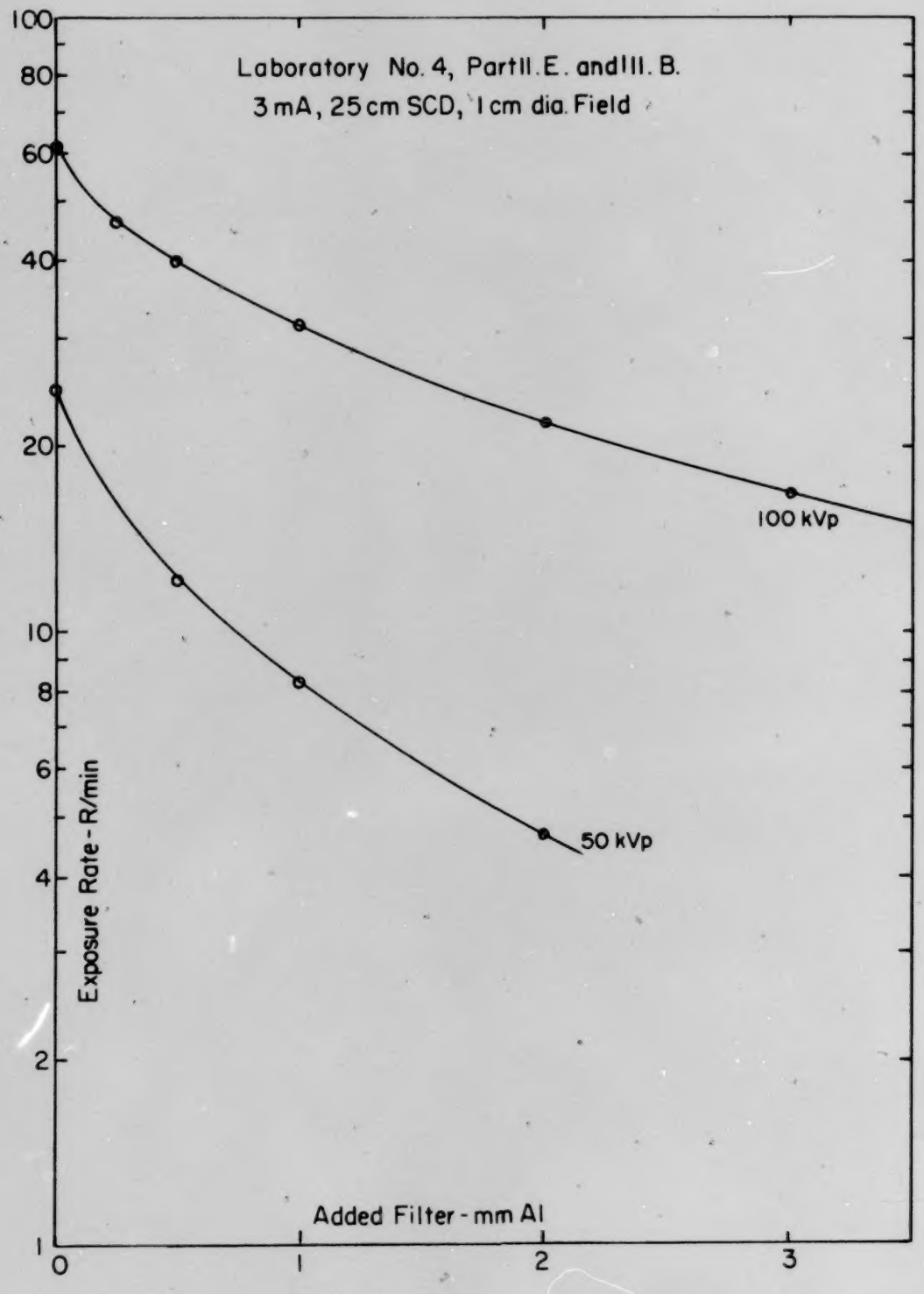
$\mu/\rho = 0.693/(\rho)\ (HVL)$
50 kVp: $\mu/\rho = 0.693/(2.7)(.047) = 5.46\ cm^2/g$

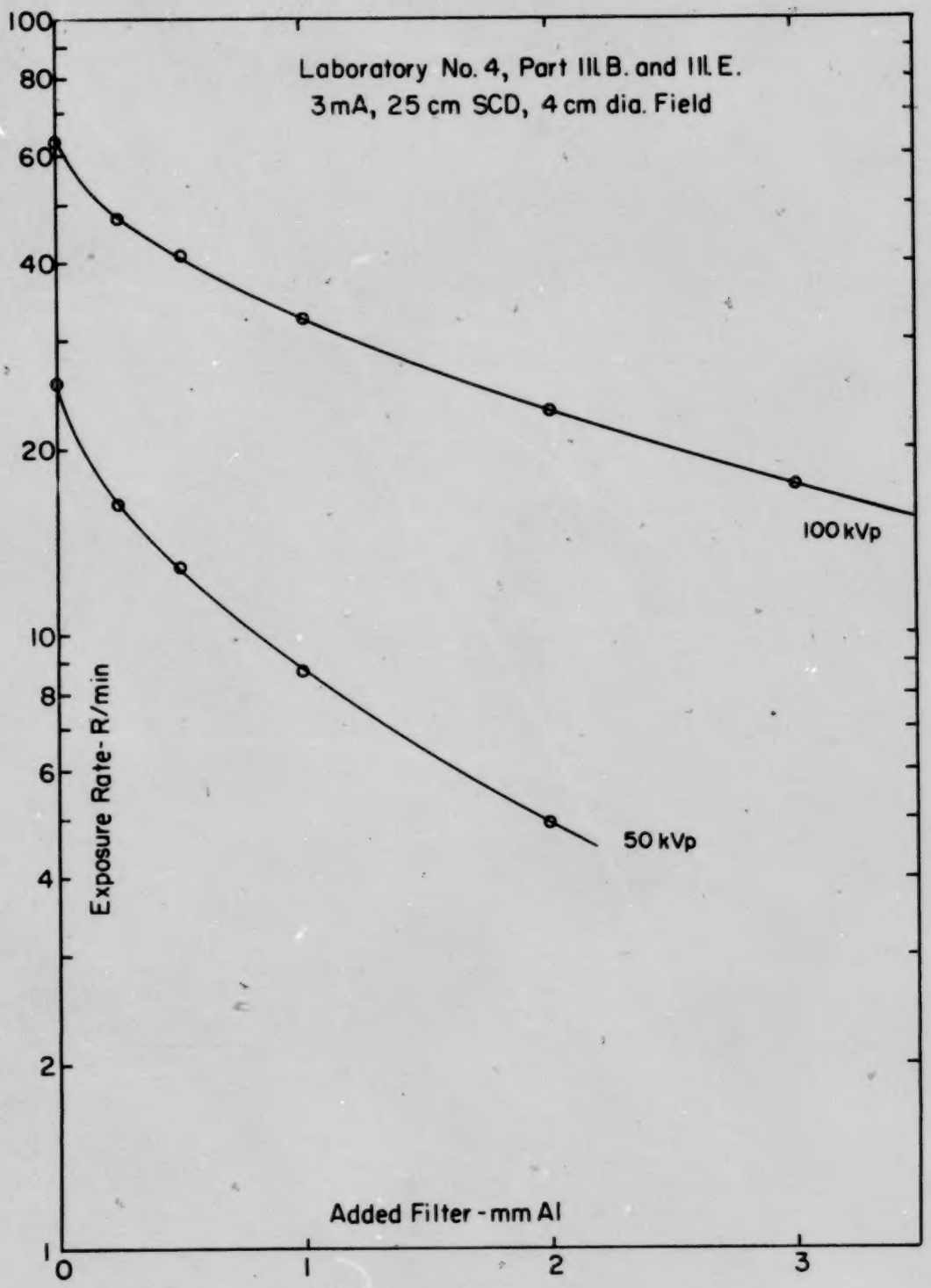
100 kVp: $\mu/\rho = 0.693/(2.7)(0.106) = 2.42\ cm^2/g$

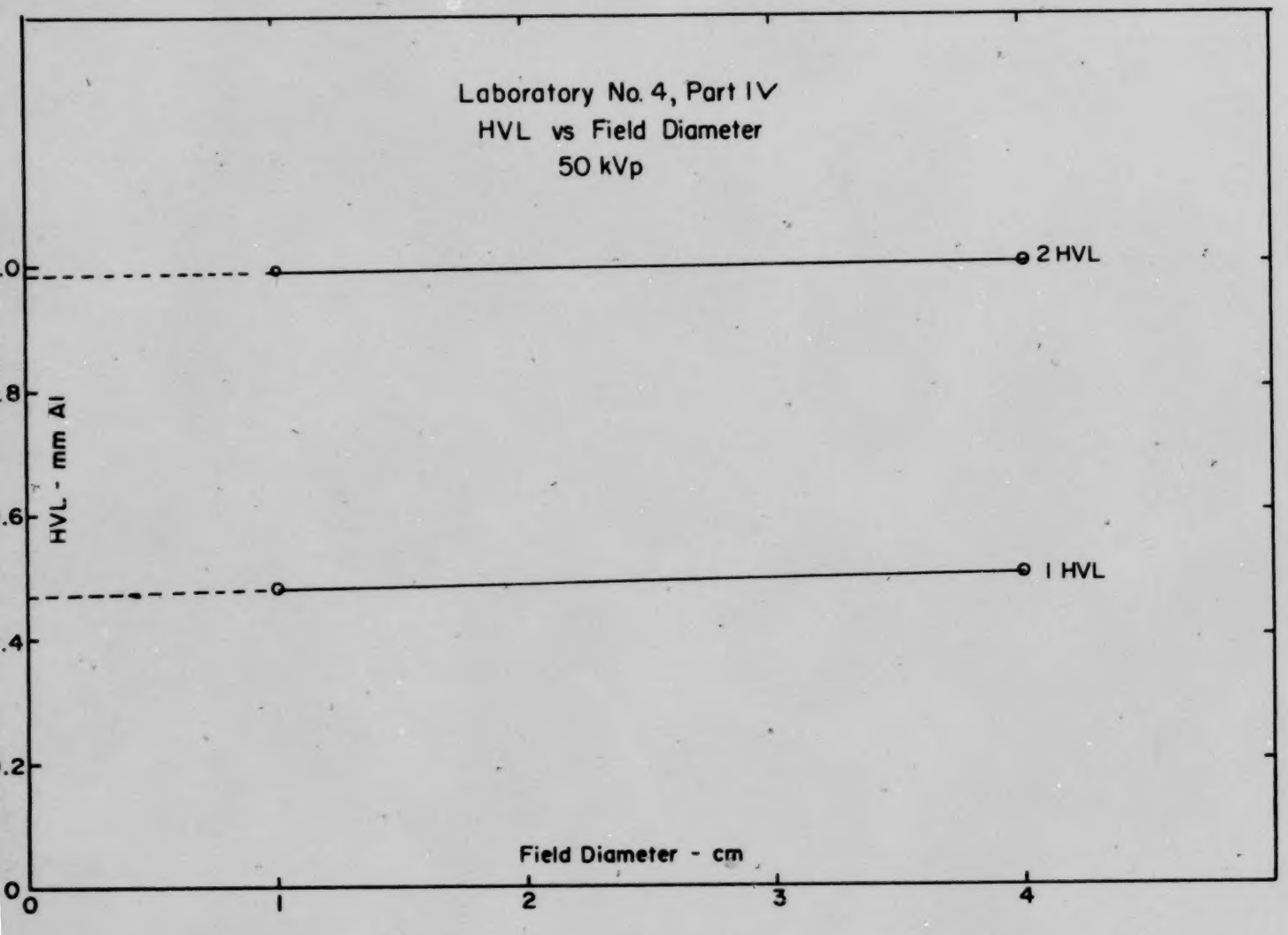
From curve:

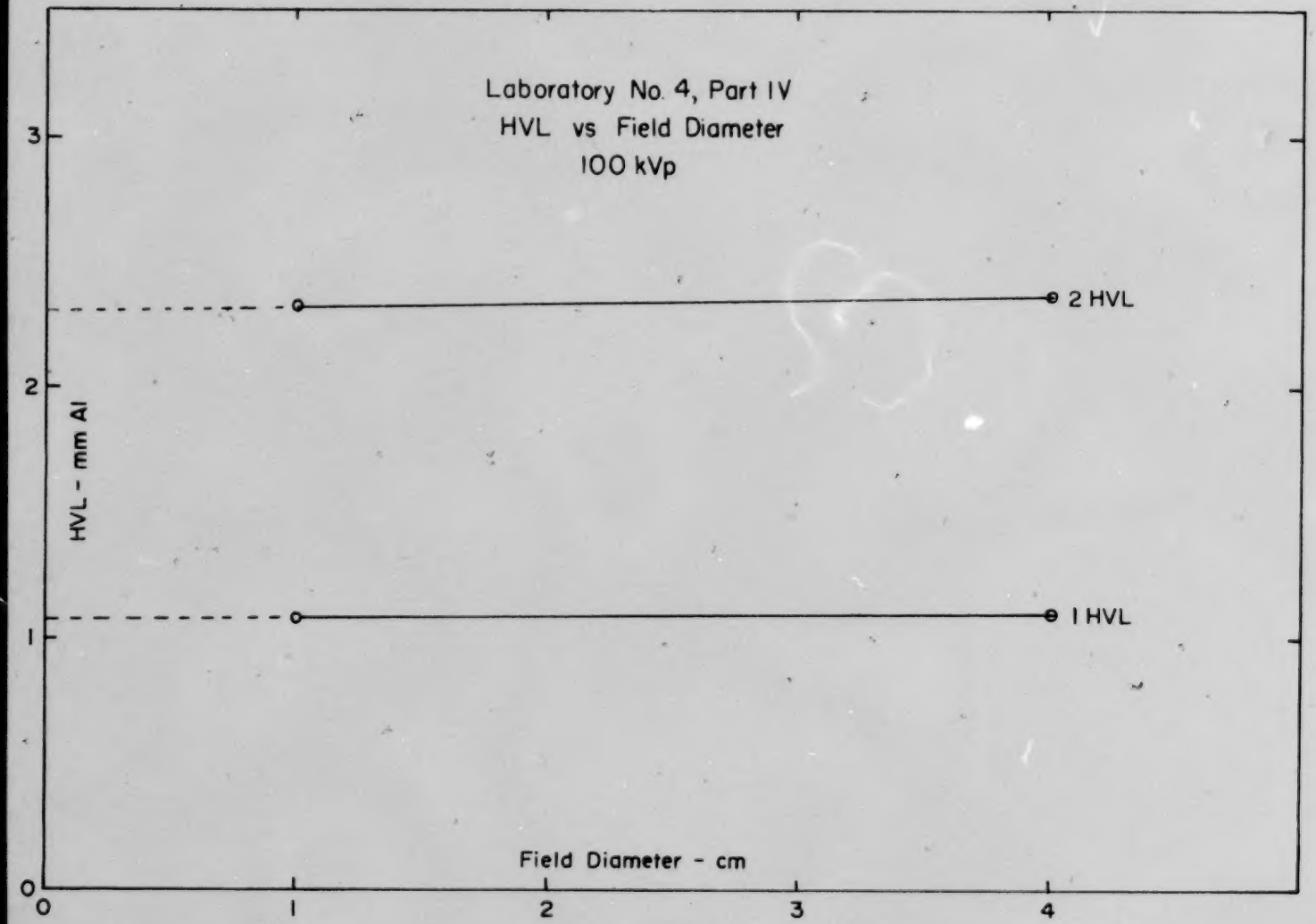
50 kVp → 18 keV

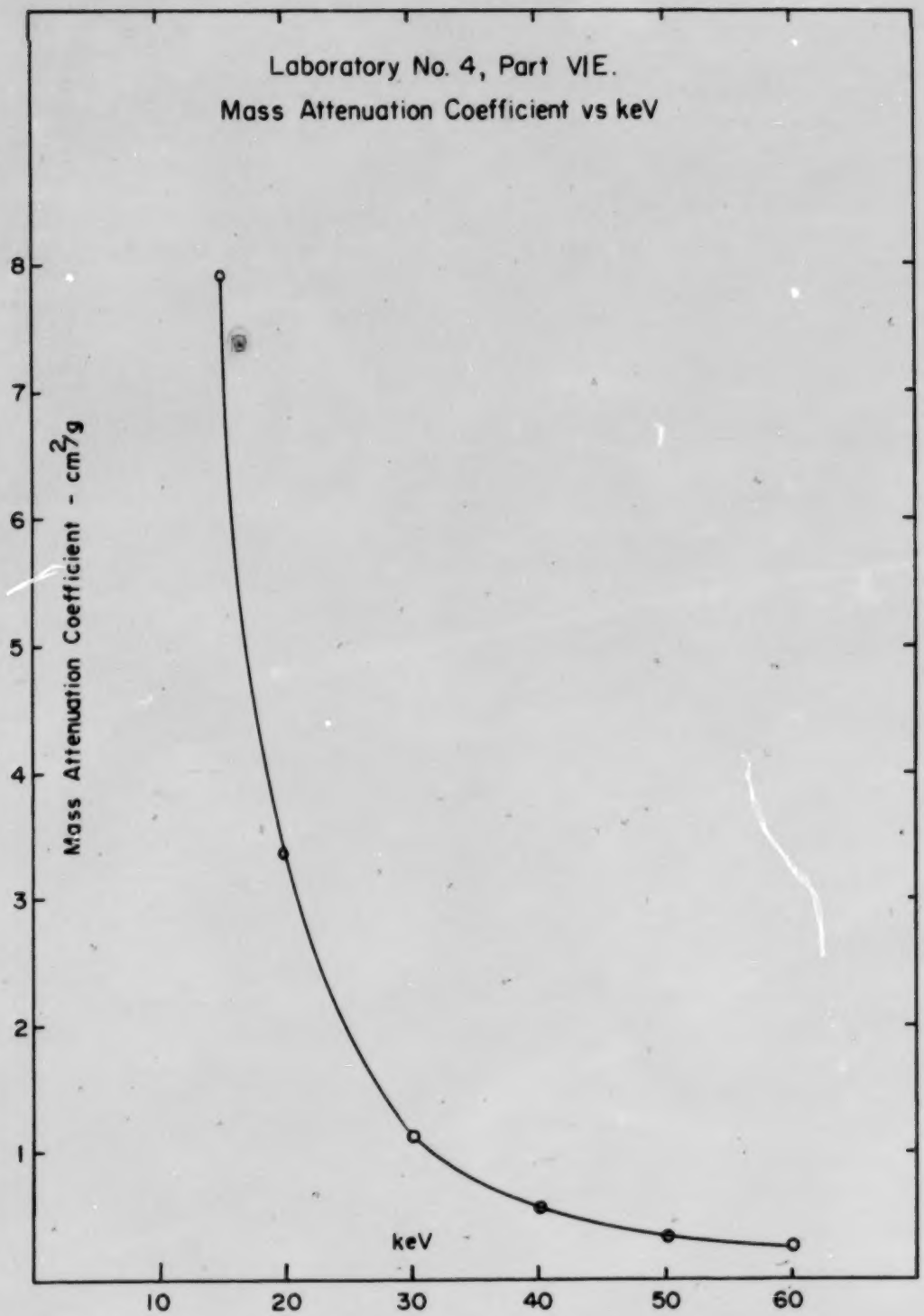
100 kVp → 21 keV


Laboratory No. 4, Part II. E. and III. B.
3 mA, 25 cm SCD, 1 cm dia. Field
100 kVp
50 kVp
Exposure Rate - R/min
Added Filter - mm Al
100
80
60
40
20
10
8
6
4
2
1
0
1
2
3


Laboratory No. 4, Part III B. and III E.
3 mA, 25 cm SCD, 4 cm dia. Field
100 kVp
50 kVp
Exposure Rate - R/min
Added Filter - mm Al
100
80
60
40
20
10
8
6
4
2
1
0
1
2
3


Laboratory No. 4, Part IV
HVL vs Field Diameter
50 kVp
2 HVL
1 HVL
HVL - mm Al
Field Diameter - cm
0
1
2
3
4


Laboratory No. 4, Part IV
HVL vs Field Diameter
100 kVp
2 HVL
1 HVL
HVL - mm Al
Field Diameter - cm
0
1
2
3
4


Laboratory No. 4, Part VIE.
Mass Attenuation Coefficient vs keV
Mass Attenuation Coefficient - cm²/g
8
7
6
5
4
3
2
1
keV
10
20
30
40
50
60

LABORATORY NO. 5

TITLE: Energy Dependence of X-Ray Measuring Instruments

PURPOSE: To study the energy dependence characteristics of several instruments used to measure exposure

TIME: 6 hours

MATERIALS FOR EACH STUDENT GROUP:

One Victoreen Model 555 Radocon II with Model 555-0.1 DAS probe
One General Electric 90 kVp mobile x-ray machine
One Victoreen Model 444 survey meter
One Victoreen Model 592B survey meter
One Victoreen Model 740B survey meter
One Nuclear Chicago Model 2588 survey meter
One Nuclear Associates Model PTW 20 mR alarm
One Victoreen Model 687C Minometer II
One Victoreen Model N 3A 0-200 mR pocket dosimeter
One Bendix Model 906-1 dosimeter charger
One Bendix NS 0-200 mR low energy pocket dosimeter
Two leaded vinyl aprons
One sheet two-cycle semi-log graph paper, K & E 46-5253 or equivalent
One sheet three-cycle semi-log graph paper, K & E 46-5493 or equivalent
One ships curve, K & E 1685-48 or equivalent

REFERENCES: Attix, Roesch, Tochilin
Radiation Dosimetry

Stanton, L.
Basic Medical Radiation Physics

LABORATORY NO. 5

5. ENERGY DEPENDENCE OF X-RAY MEASURING INSTRUMENTS

I. INTRODUCTION

There are several factors which may result in the failure of a radiation measuring instrument to indicate the true exposure in a radiation field. These include time response, temperature and pressure (for unsealed chambers), field distribution, exposure rate and photon energy. The purpose of this laboratory exercise is to investigate the dependence of several x-ray measuring instruments on one of these factors, photon energy.

An x-ray measuring instrument is said to exhibit energy dependence if the ratio of true exposure to indicated exposure is not unity as a function of energy. Factors contributing to energy dependence of instruments include:

1. Improper chamber wall thickness
2. Non-air-equivalent chamber wall

Ion chambers are usually designed for operation over a specified energy range with a specified energy response (± 2%, ± 5%, ± 10%, etc.) over this range. Most of the instruments investigated in this laboratory exercise are not designed for use in the low energy range provided by the 90 kVp x-ray machine used in this laboratory exercise. As a result, there are significant changes in instrument response over the range of x-ray energies used in this laboratory exercise.

II. EQUIPMENT

A. General Electric 90 kVp mobile x-ray machine

B. Victoreen Model 555 Radocon II with Model 555-0.1 probe

C. Victoreen Model 444 survey meter

D. Victoreen Model 592B survey meter

E. Victoreen Model 740B survey meter

F. Victoreen Model 440 survey meter

G. Nuclear Chicago Model 2588 survey meter

H. Nuclear Associates Model PTW 20 mR alarm

I. Victoreen Model 687C Minometer II

J. Victoreen Model N3A 0-200 mR pocket chamber

K. Bendix Model 906-1 dosimeter charger/reader

L. Bendix Model NS 0-200 mR dosimeter

M. Bendix Model 1200-MR 0-200 mR dosimeter

III. INTEGRATING INSTRUMENTS

CAUTION: Special consideration must be paid to the protection of personnel whenever x-ray equipment is operated outside a shielded enclosure. The use of mobile protective shields and the wearing of protective aprons can be effective in providing adequate personnel protection.

A. Expose the 555 Radocon II on the 0-300 mR scale, the Victoreen 444 on the 0-300 mR scale, the Nuclear Chicago 2588 on the 250 mR scale, the self-reading pocket dosimeters, the pocket chamber, and the 20 mR alarm at the following settings:

kVp	mA	Added mm Al Filter	Effective energy - keV
50	3	0	14.5
60	3	0	15.0
90	3	0	16.5
50	3	0.5	20.5
70	3	0.5	22.5
85	3	0.5	23.5
70	3	1.0	24.5
85	3	1.0	26.5
70	3	2.0	29.0
90	3	3.0	30.5

B. Select distance and exposure times to provide a 1/2 scale response (150-200 mR) using the 555 Radocon II

C. Calculate the correction factors for each instrument using the 555 Radocon as the standard. (The correction factor for the 555 Radocon II is essentially unity over the energy range involved)

$$\text{Correction Factor} = \frac{\text{555 Radocon Reading}}{\text{Instrument Reading}}$$

D. On the same sheet of graph paper plot correction factors versus keV for each instrument used

IV. SURVEY INSTRUMENTS

A. Expose the 555 Radocon and the survey instruments to the same x-ray machine settings used in Section III

B. Choose a distance to provide 1/2 - 2/3 full scale response on the 555 Radocon

C. Calculate correction factors for each instrument using the 555 Radocon as a standard

D. Plot correction factors versus keV as in Section III

V. QUESTIONS

A. Explain how one would use these experimental results in actual practice.

B. Why does the model NS pocket dosimeter have poorer energy dependence characteristics than the pocket chamber or the low energy pocket dosimiter?

LABORATORY NO. 5

DATA SHEET

I. INTEGRATING INSTRUMENTS

Effective Energy keV	Exposure Time sec	Radocon 555 mR	Victoreen 444 mR	Victoreen 444 C.F.	Victoreen N3A Pocket Cham. mR	Victoreen N3A Pocket Cham. C.F.
14.5						
15.0						
16.5						
20.5						
22.5						
23.5						
24.5						
26.5						
29.0						
30.5						

Bendix NS Dosimeter mR	Bendix NS Dosimeter C.F.	Bendix 1200-MR Pocket Dosim. mR	Bendix 1200-MR Pocket Dosim. C.F.	Nuclear Chicago 2588 mR	Nuclear Chicago 2588 C.F.	Nuclear Associates PTW mR	Nuclear Associates PTW C.F.

II. SURVEY (Rate) INSTRUMENTS

Effective Energy keV	Radocon 555 mR/h	Victoreen 444 mR/h	Victoreen 444 C.F.	Victoreen 740 mR/h	Victoreen 740 C.F.	Victoreen 592B mR/h	Victoreen 592B C.F.
14.5							
15.0							
16.5							
20.5							
22.5							
23.5							
24.5							
26.5							
29.0							
30.5							

LABORATORY NO. 5

TYPICAL DATA

I. INTEGRATING INSTRUMENTS

Effective Energy keV	Radocon 555		Victoreen 444		Bendix NS Dosimeter		Vict. N3A Chamber		Bendix 1200-MR Dosimeter	
	mR	C.F.	mR	C.F.	mR	C.F.	mR	C.F.	mR	C.F.
14.5	150	1.00	125	1.20	18	8.35	54	2.78	139	1.08
15.0	150	1.00	125	1.20	24	6.28	57.5	2.57	139	1.08
16.0	150	1.00	127	1.18	34.5	4.32	65.5	2.30	143	1.05
20.5	150	1.00	131	1.14	47	3.20	83	1.80	149	1.01
22.5	150	1.00	135	1.11	52	2.90	94	1.60	150	1.00
23.5	150	1.00	137	1.10	54.5	2.75	97	1.55	150	1.00
24.5	150	1.00	139	1.08	66	2.28	103	1.45	150	1.00
26.5	150	1.00	147	1.02	86	1.75	106	1.41	150	1.00
29.0	150	1.00	150	1.00	99	1.51	117	1.28	151	0.99
30.5	150	1.00	153	0.98	120	1.25	131	1.15	152	0.99

Nuclear Chicago 2588		Nuclear Associates PTW	
mR	CF	mR*	CF
152	.99	104	5.2
158	.95	81	4.06
168	.89	59	2.96
161	.93	70	3.5
165	.91	52	2.6
172	.87	43.5	2.17
163	.92	46	2.3
165	.91	42	2.1
153	.98	40	1.99
160	.94	37	1.85

* mR to trigger 20 mR alarm

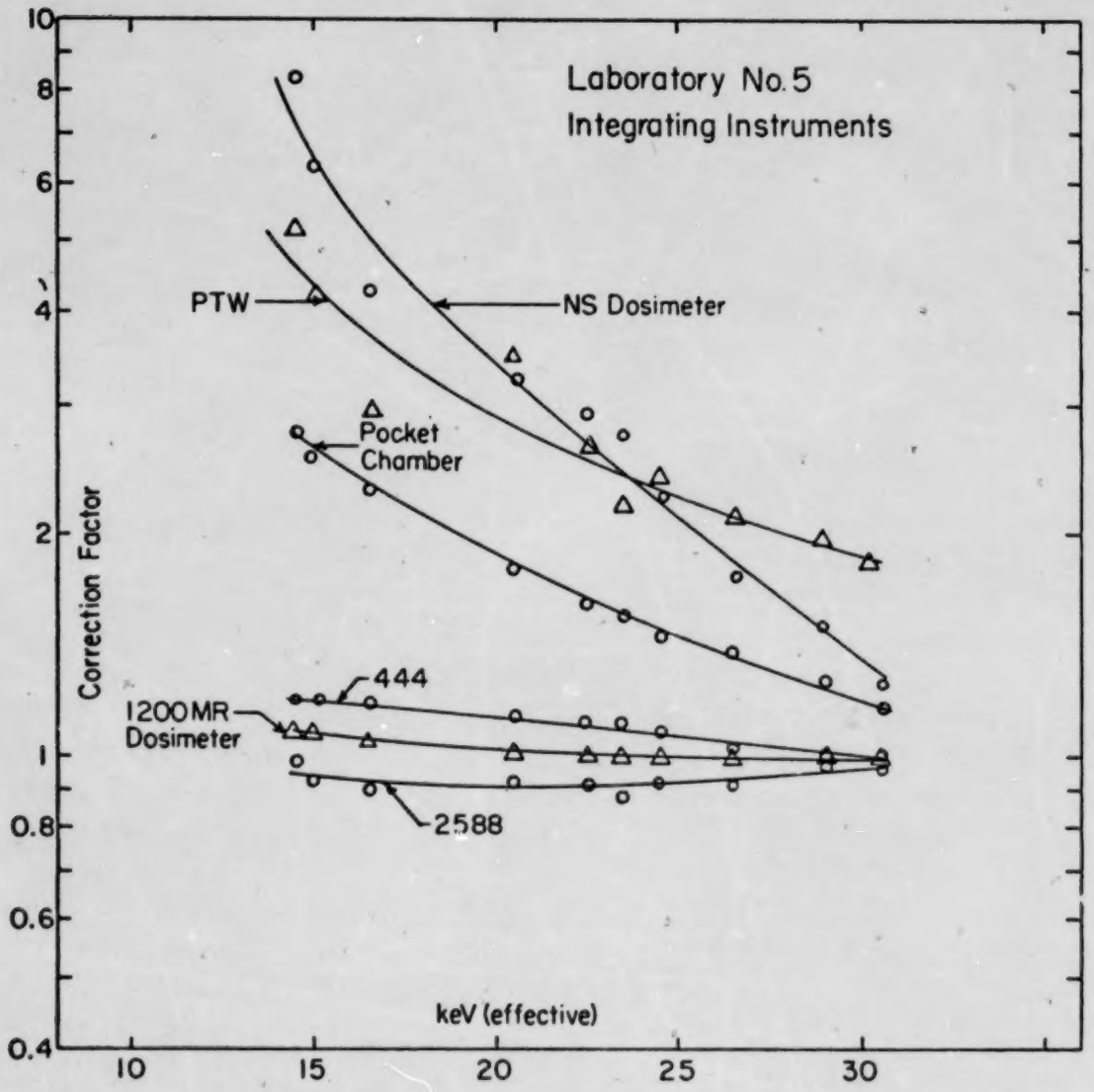
II. SURVEY INSTRUMENTS

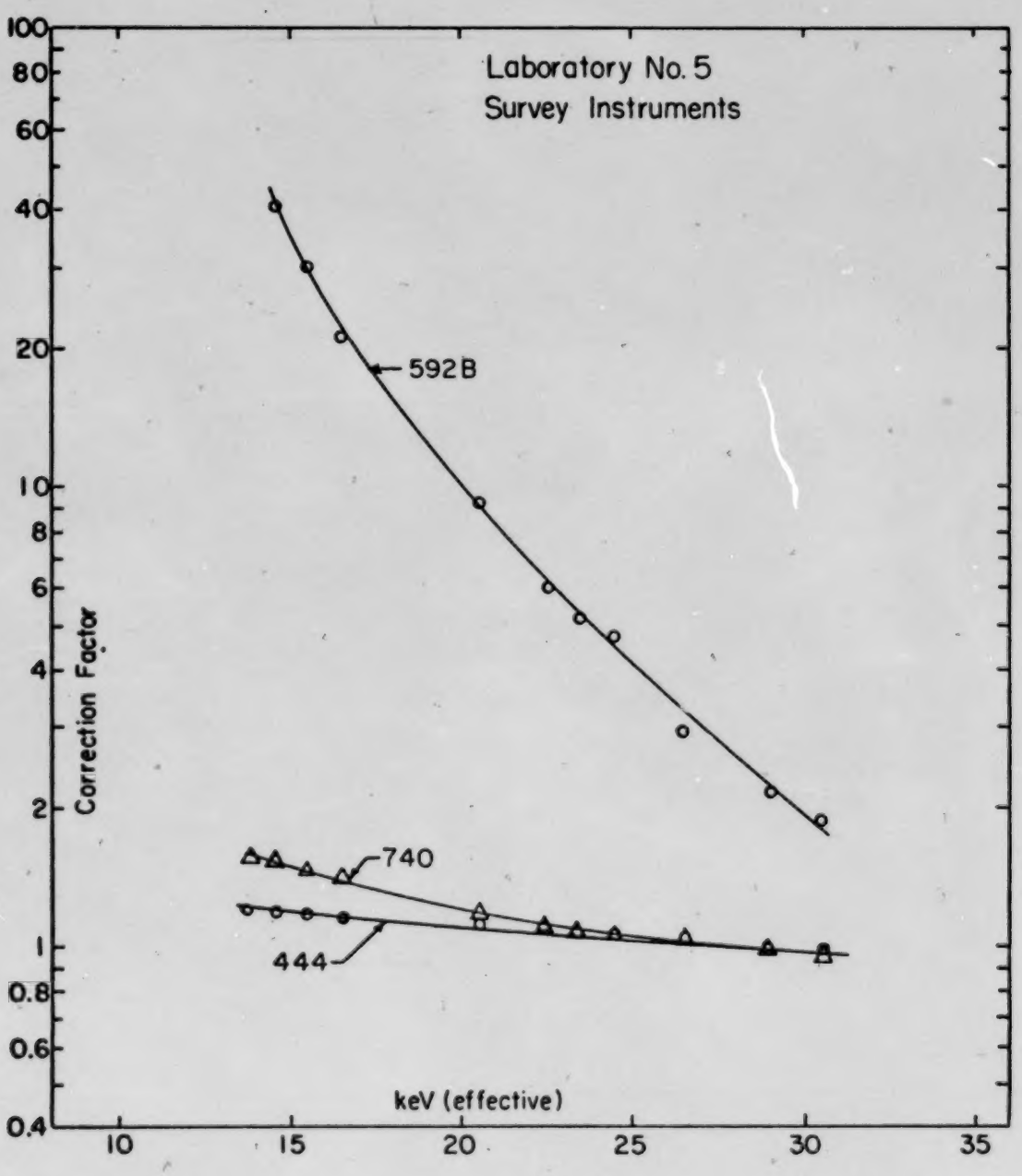
Effective Energy keV	Radocon 555 R/h	Radocon 555 C.F.	Victoreen 444 R/h	Victoreen 444 C.F.	Victoreen 740 R/h	Victoreen 740 C.F.	Victoreen 592B R/h	Victoreen 592B C.F.
14.5	0.96	1.00	0.80	1.20	0.63	1.52	0.024	40.7
15.0	0.75	1.00	0.63	1.19	0.49	1.52	0.025	30.2
16.5	1.50	1.00	1.26	1.18	1.03	1.45	0.072	21.0
20.5	2.25	1.00	1.96	1.15	1.87	1.20	0.25	9.00
22.5	1.45	1.00	1.32	1.10	1.29	1.12	0.24	6.10
23.5	1.50	1.00	1.37	1.10	1.37	1.10	0.29	5.20
24.5	1.90	1.00	1.78	1.07	1.78	1.07	0.41	4.67
26.5	1.90	1.00	1.86	1.02	1.86	1.02	0.65	2.92
29.0	1.60	1.00	1.60	1.00	1.62	0.99	0.75	2.14
30.5	1.30	1.00	1.32	0.99	1.33	0.98	0.70	1.87

III. ANSWERS TO QUESTIONS

A. If the effective energy of the radiation source is known, these data would tell which instrument to use without a significant coorection factor or what the correction factor is for a particular instrument. If the range of energies only is known the data would tell which instrument to use for the greatest overall accuracy.

B. The NS pocket dosimeter is not designed for use below about 80 keV, whereas, the pocket chamber is designed for use down to 30 keV. The wall of the pocket dosimeter is not "air equivalent" (it is too thick) at the low energies.


Laboratory No. 5
Integrating Instruments
PTW
NS Dosimeter
Pocket
Chamber
444
1200MR
Dosimeter
2588
Correction Factor
keV (effective)
10
8
6
4
2
1
0.8
0.6
0.4
10
15
20
25
30


Laboratory No. 5
Survey Instruments
592B
740
444
Correction Factor
keV (effective)
100
80
60
40
20
10
8
6
4
2
1
0.8
0.6
0.4
10
15
20
25
30
35

LABORATORY NO. 6

TITLE: Response Time of Survey Instruments

PURPOSE: To determine the response time of typical survey instruments

TIME: 3 hours

MATERIALS FOR EACH STUDENT GROUP:

One General Electric 90 kVp mobile x-ray machine
One Victoreen model 440 survey meter
One Victoreen model 740B survey meter
One Victoreen model 444 survey meter
One Victoreen model 592 B survey meter
One Nuclear Chicago model 2588 survey meter
One Victoreen Thyac GM counter
One Victoreen model 440 RF/C survey meter
Two leaded vinyl aprons
Seven sheets linear graph paper, K & E 46-0703 or equivalent
One ships curve, K & E 1685-48 or equivalent

REFERENCES: Survey meter instruction manuals

LABORATORY NO. 6

6. SURVEY INSTRUMENT RESPONSE TIME

I. INTRODUCTION

The survey instruments that will be used in this laboratory exercise are devices which measure the current produced by ionization within a confined volume of air. This current is proportional to exposure rate and the readout is in this form. For a particular exposure rate it takes the instrument a certain time to reach a final steady-state reading. This response time is influenced by two factors:

1. The R C time constant of the circuit and
2. The inertia of the meter movement.

The R C time constant is usually the limiting factor. The time constant, resistance in ohms times capacitance in farads, is that time in seconds for the meter to indicate 63 percent of its final steady-state reading (assuming no meter movement inertia effects). In ionization chamber survey meters, C is the sum of the chamber capacitance and the distributed capacitance of the associated circuitry, and R is usually the chamber load resistor. In this type of instrument, the sensitivity is often changed by switching in more or less load resistance. Therefore, the time constant may be different from one range (sensitivity) to another. A simplified diagram is shown in figure 1. (V(t) refers to the voltage at time t.)

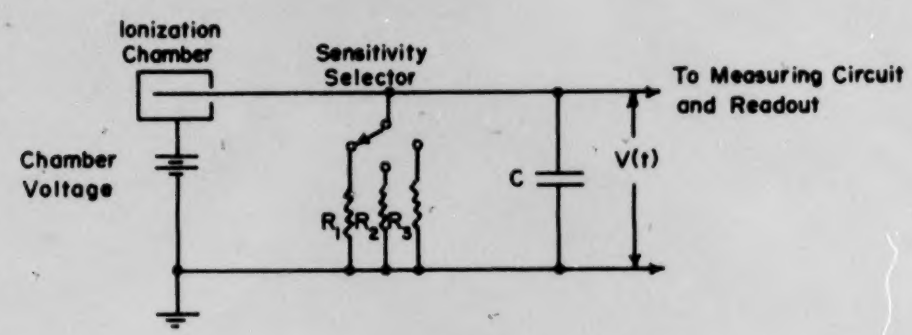


Figure 1

The voltage V(t) is directly proportional to the meter reading. If V(f) is the final steady-state value for a particular ionization current, then V(t) is given by:

$$V(t) = V(f)\ (1 - e^{-t/RC})$$

The ration V(t)/V(f) represents the fraction of the final steady-state value as read on the meter. When t = RC = time constant:

$$V(t)/V(f) = (1 - e^{-1}) = 1 - 0.37 = 0.63$$

If the percent of steady-state reading versus exposure time is plotted, the time constant can be determined from the curve where the meter response is 63 percent of the final steady-state value. Meter movement inertia will cause this curve to deviate from the ideal.

II. EQUIPMENT

A. General Electric 90 kVp mobile x-ray machine

B. Victoreen survey meters

1. Model 440
2. Model 740B
3. Model 444
4. Model 592B
5. MOdel 440 RF/C
6. Thyac

C. Nuclear Chicago 2588

III. PROCEDURE

CAUTION: Special consideration must be paid to the protection of personnel whenever x-ray equipment is operated outside a shielded enclosure. The use of mobile protective shields and wearing of protective aprons can be effective in providing adequate personnel protection.

A. Adjust the x-ray machine settings (kVp, mA) and geometry (filter and distance) to provide 90-100 percent full-scale response for each range on each survey meter used

B. Determine the time response of the survey meters by recording the meter readings at exposure times from 0.1 second to a time at least equal to the time necessary for steady-state response (this may require times up to 30 sec.)

C. On long exposures where the meter may reach a peak reading and then decrease to a steady-state value, record both these values

D. Plot response curves for each of the survey meters, percent steady-state reading versus exposure time, and determine the time constant for each meter scale

IV. QUESTIONS

A. Of what importance is a knowledge of the time response characteristics of survey meters in the selection of a survey meter for a particular application?

B. Why is it desirable to have a complete time response curve rather than only the value of the survey meter time constant?

C. In changing to a more sensitive scale (e.g. from 100 mR/h to 3 mR/h) will the value of the load resistor increase or decrease? Explain.

LABORATORY NO. 6

DATA SHEETS

1. Victoreen 740 B Survey Meter

Scale								
25 mR/h (X 1)			250 mR/h (X 10)			2500 mR/h (X 100)		
Time-sec	Reading	%SS	Time-sec	Reading	%SS	Time-sec	Reading	%SS

II. Victoreen 440 Survey Meter

Scale								
3 mR/h			10 mR/h			30 mR/h		
Time	Reading	%SS	Time	Reading	%SS	Time	Reading	%SS

Scale					
100 mR/h			300 mR/h		
Time	Reading	%SS	Time	Reading	%SS

III. Victoreen 444 Survey Meter

Scale								
3 mR/h			10 mR/h			30 mR/h		
Time	Reading	%SS	Time	Reading	%SS	Time	Reading	%SS

Scale					
100 mR/h			300 mR/h		
Time	Reading	%SS	Time	Reading	%SS

IV. Victoreen 592 Survey Meter

Scale								
10 mR/h (X1)			100 mR/h (X10)			1000 mR/h (X100)		
Time	Reading	%SS	Time	Reading	%SS	Time	Reading	%SS

V. , Victoreen 440 RF/C Survey Meter

Scale								
1 mR/h			3 mR/h			10 mR/h		
Time	Reading	%SS	Time	Reading	%SS	Time	Reading	%SS

Scale					
30 mR/h			100 mR/h		
Time	Reading	%SS	Time	Reading	%SS

VI. Nuclear Chicago 2588 Survey Meter

Scale								
25 mR/h			250 mR/h			2500 mR/h		
Time	Reading	%SS	Time	Reading	%SS	Time	Reading	%SS

VII. Victoreen Thyac GM Counter

Response								
Slow			Medium			Fast		
Time	Reading	%SS	Time	Reading	%SS	Time	Reading	%SS

LABORATORY NO. 6

TYPICAL DATA

I. Victoreen 740 Survey Meter

Scale								
25 mR/h (X1)			250 mR/h (X 10)			2500 mR/H (X 100)		
Time-sec	Reading	Percent	Time-sec	Reading	Percent	Time-sec	Reading	Percent
1	2	10.5	0.2	20	10	0.3	375	17.5
2	4	20.5	0.5	45	22	0.5	600	28
3	6	31	0.8	75	36.5	0.8	900	42
4	7.5	38.5	1	90	44	1.1	1150	53.5
5	9	46	1.3	115	56	1.4	1350	62.5
7	11.8	60.5	1.6	135	66	1.8	1550	72
9	14	72	2	150	73	2.3	1750	81.5
10.5	15	77	2.3	160	78	2.8	1950	91
12.5	17.5	90	2.8	175	85.5	3.5	2050	95.5
16	19.5	100	3	175	85.5	4	2150	100
20	20.3	104	3.5	200	97.5	4.5	2150	100
24	19.5	100	4	195	95	5	2150	100
28	19.5	100	4.5	195	95	6	2150	100
32	19.5	100	5.5	200	97.5	7	2150	100
			6	205	100			
			6.5	205	100			
			10	205	100			

II. Victoreen 440 Survey Meter

Scale								
3 mR/h			10 mR/h			30 mR/h		
Time-sec	Reading	Percent	Time-sec	Reading	Percent	Time-sec	Reading	Percent
0.5	0.31	14	0.3	1.8	21.5	0.4	7.9	31.5
0.8	0.52	23.5	0.5	2.7	32	0.5	8.5	34
1	0.70	32	0.8	3.9	46.5	0.8	14.5	57.5
1.3	0.91	41.5	1	5.0	59.5	1	16.5	65.5
1.5	0.95	43	1.2	5.4	64.5	1.3	20	79.5
2	1.22	55.5	1.5	6.4	76	1.5	22.5	84.5
2.5	1.46	66.5	1.8	6.9	82	1.8	24.1	95.5
3	1.50	68.8	2	7.0	83.5	2	25.0	99
3.5	1.64	74.5	2.5	7.6	91.5	2.5	26.0	103
4	1.8	82	3	7.8	93	3	26.0	103
5	1.92	87	3.5	8.1	96.5	3.5	25.2	100
6	2.15	97.5	4	8.2	97.5	4	25.2	100
7	2.20	100	4.5	8.4	100	5	25.2	100
8	2.20	100	5	8.6	102.5			
9	2.20	100	6	8.3	99			
10	2.20	100	7	8.4	100			
			10	8.4	100			

II. Victoreen 440 Survey Meter (continued)

Scale					
100 mR/H			300 mR/h		
Time-sec	Reading	Percent	Time-sec	Reading	Percent
0.3	24	24.5	0.3	68	25.5
0.5	38	39	0.5	105	39
0.8	61	62	0.8	155	57.5
1	73	74.5	1	188	70
1.5	98	100	1.5	240	89
2	103	105	2	265	99
3	98	100	2.5	262	97.5
3.5	97	99	3	280	104
4	98	100	3.5	267	99
5	98	100	4	269	100
			5	269	100

III. Victoreen 444 Survey Meter

Scale								
3 mR/h			10 mR/h			30 mR/h		
Time-sec	Reading	Percent	Time-sec	Reading	Percent	Time-sec	Reading	Percent
0.5	0.5	18.5	1	2.5	29	0.5	5	20
1	1.1	40.5	2	4.5	52.5	1	10	39.5
1.5	1.65	61	3	5.7	66.5	1.5	14.2	56
2	1.84	68	4	7.1	82.5	2	18	71
2.5	2.25	83.5	5	7.4	86	2.5	20	79
3	2.52	93.5	6	8.0	93	3	22.5	89
3.5	2.55	94.5	7	8.5	99	3.5	25	99
4	2.70	100	8	8.3	96.5	4	25	99
4.5	2.75	102	9	8.6	100	4.5	26	103
5	2.70	100	10	8.6	100	5	25.4	101
5.5	2.70	100				5.5	25.2	99.5
						6	25.3	100

III. Victoreen 444 Survey Meter (continued)

Scale					
100 mR/h			300 mR/h		
Time-sec	Reading	Percent	Time-sec	Reading	Percent
0.5	26	30	0.5	75	30
1	48.5	55	1	140	56.5
1.5	66	76	1.5	185	74.5
2	77	87.5	2	220	88.5
2.5	82.5	94	2.5	235	95
3	86.5	98.5	3	242	97
4	88.5	101	3.5	246	99
5	88.2	100.5	4	252	102
6	88	100	4.5	252	102
7	88	100	5	246	99
8	88	100	6	247	99.5
10	88	100	7	248	100
			10	248	100

IV. Victoreen 592B Survey Meter

Scale								
10 mR/h (X 1)			100 mR/h (X 10)			1000 mR/h (X 100)		
Time-sec	Reading	Percent	Time-sec	Reading	Percent	Time-sec	Reading	Percent
0.5	3.4	38.5	0.2	23	27	0.2	250	28
1	5.7	65	0.5	46	53.3	0.5	520	58
1.5	7.3	83	0.8	64	74.5	0.8	700	78
2	8.1	92	1	71	82.5	1	760	84.5
2.5	8.3	94.5	1.5	81	94	1.5	860	95.5
3	8.5	96.5	2	84	99	2	880	98
3.5	8.8	100	2.5	87	101	2.5	910	101
4	9.0	102.5	3	86	100	3	910	101
4.5	9.0	102.5	3.5	86	100	4	900	100
5	8.8	100	4	86	100	5	900	100
6	8.8	100	5	86	100			

IVa. Victoreen Thyac GM Counter

Response Selector								
Slow			Medium			Fast		
Time-sec	Reading	Percent	Time-sec	Reading	Percent	Time-sec	Reading	Percent
1	0.39	21.7	0.5	0.42	25.4	0.2	0.4	21.6
2	0.72	40	1	0.8	48.5	0.5	0.85	45.9
3	0.98	54.4	2	1.15	69.7	1	1.4	75.7
5	1.3	72.2	3	1.4	84.8	2	1.85	100
8	1.55	86.1	5	1.6	97	3	1.85	100
10	1.7	94.4	8	1.65	100	5	1.85	100
15	1.8	100	10	1.65	100			
20	1.8	100						

IVb. Nuclear Chicago 2588 Survey Meter

Scale								
25 mR/h			250 mR/h			2500 mR/h		
Time-sec	Reading	Percent	Time-sec	Reading	Percent	Time-sec	Reading	Percent
0.3	4.5	31	0.1	25	11.2	0.1	250	10.4
0.5	7	48.3	0.3	60	26.9	0.3	600	25
1	12	82.7	0.5	95	42.6	0.5	1000	41.7
1.2	12	82.7	0.8	140	62.8	0.8	1500	62.5
1.5	13	89.6	1	160	71.7	1	1750	72.9
2	14	96.5	1.5	200	89.7	1.5	2150	89.5
3	14.5	100	2	210	94.2	2	2300	95.9
5	14.5	100	3	220	98.6	3	2400	100
			5	223	100	5	2400	100
			8	223	100			

IVc. Victoreen 440 RF/C Survey Meter

Scale

1 mR/h			3 mR/h			10 mR/h		
Time-sec	Reading	Percent	Time-sec	Reading	Percent	Time-sec	Reading	Percent
1	0.26	28.2	1	0.6	27.3	1	2.4	24
1.5	0.3	32.6	1.5	0.7	31.8	1.5	3.4	34
2	0.38	41.3	2	1.0	45.5	2	4.4	44
3	0.5	54.3	3	1.4	63.7	3	6	60
4	0.74	80.5	4	1.6	72.8	4	7.4	74
5	0.8	87	5	1.75	79.5	5	8	80
7	0.96	105	8	2	91	8	9.2	92
10	0.92	100	10	2.15	98	10	9.6	96
15	0.92	100	15	2.2	100	15	10	100
			20	2.2	100	20	10	100

IVd. Victoreen 440 RF/C Survey Meter (continued)

Scale

30 mR/h			100 mR/h		
Time-sec	Reading	Percent	Time-sec	Reading	Percent
1	6.5	24.1	1	21	22.8
1.5	9.5	35.2	1.5	32	34.8
2	13	48.2	2	40	43.5
3	17	63	3	58	63.1
4	21.5	79.6	4	68	74
5	23.5	87	5	77	83.7
8	27	100	8	88	95.6
10	27	100	10	90	97.8
			15	92	100
			20	92	100

V. Survey Meter Time Constant

Instrument	Range	Time Constants-sec
Victoreen 740	25 mR/h (x1)	7.5
Victoreen 740	250 mR/h (x10)	1.6
Victoreen 740	2500 mR/h (x100)	1.4
Victoreen 440	3 mR/h	2.4
Victoreen 440	10 mR/h	1.1
Victoreen 440	30 mR/h	0.9
Victoreen 440	100 mR/h	0.8
Victoreen 440	300 mR/h	0.9
Victoreen 444	3 mR/h	2.6
Victoreen 444	10 mR/h	1.6
Victoreen 444	30 mR/h	1.6
Victoreen 444	100 mR/h	1.2
Victoreen 444	300 mR/h	1.2
Victoreen 592B	10 mR/h (x1)	0.95
Victoreen 592B	100 mR/h (x10)	0.65
Victoreen 592B	1000 mR/h (x100)	0.55
Victoreen Thyac	slow	3.8
Victoreen Thyac	medium	1.6
Victoreen Thyac	fast	0.8
Nuclear Chicago 2588	25 mR/h	0.75
Nuclear Chicago 2588	250 mR/h	0.85
Nuclear Chicago 2588	2500 mR/h	0.85
Victoreen 440 RF/C	1 mR/h	2.9
Victoreen 440 RF/C	3 mR/h	3.2
Victoreen 440 RF/C	10 mR/h	3.2
Victoreen 440 RF/C	30 mR/h	2.9
Victoreen 440 RF/C	100 mR/h	3.2

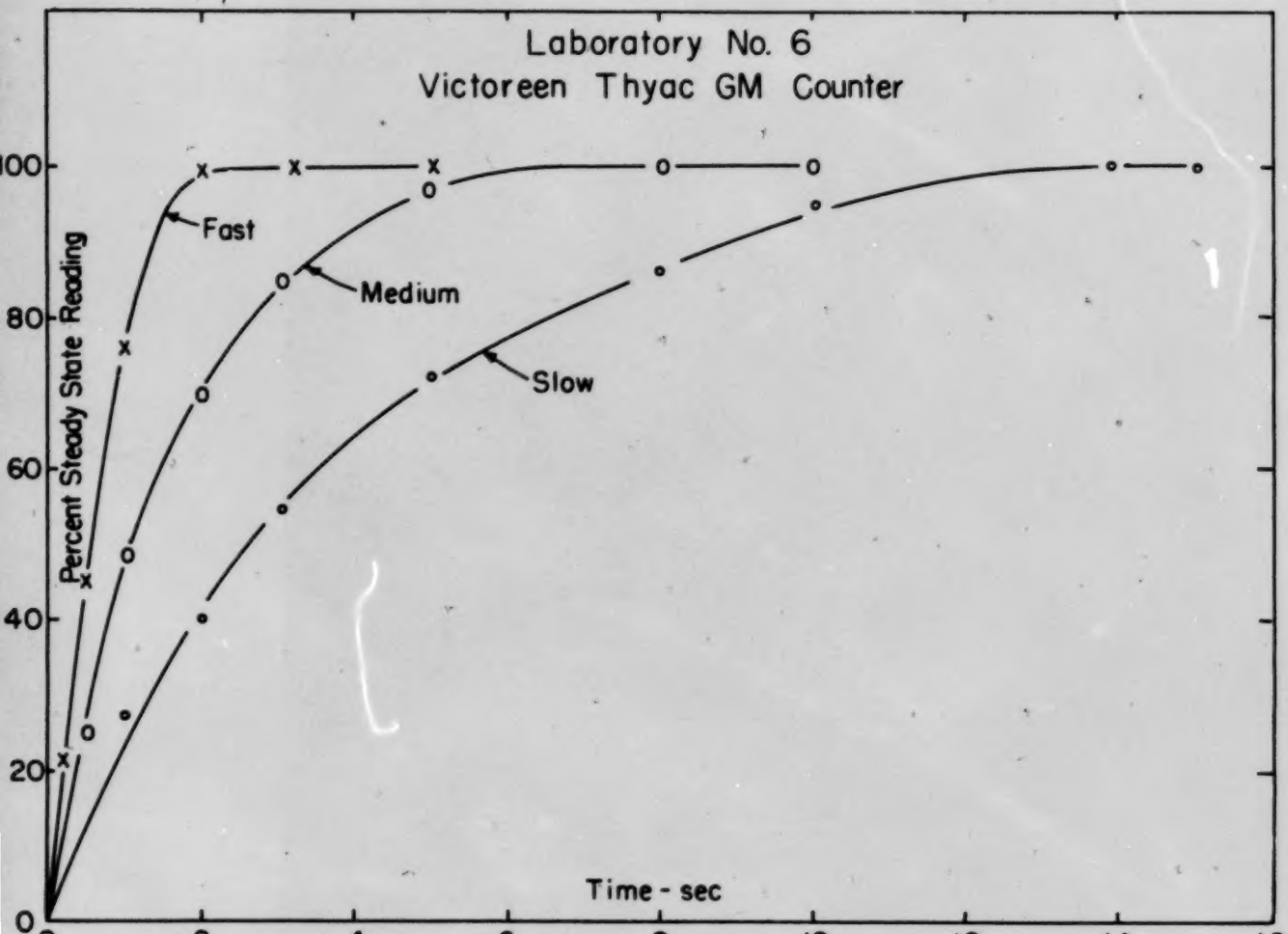
GS-462 LABORATORY NO. 6

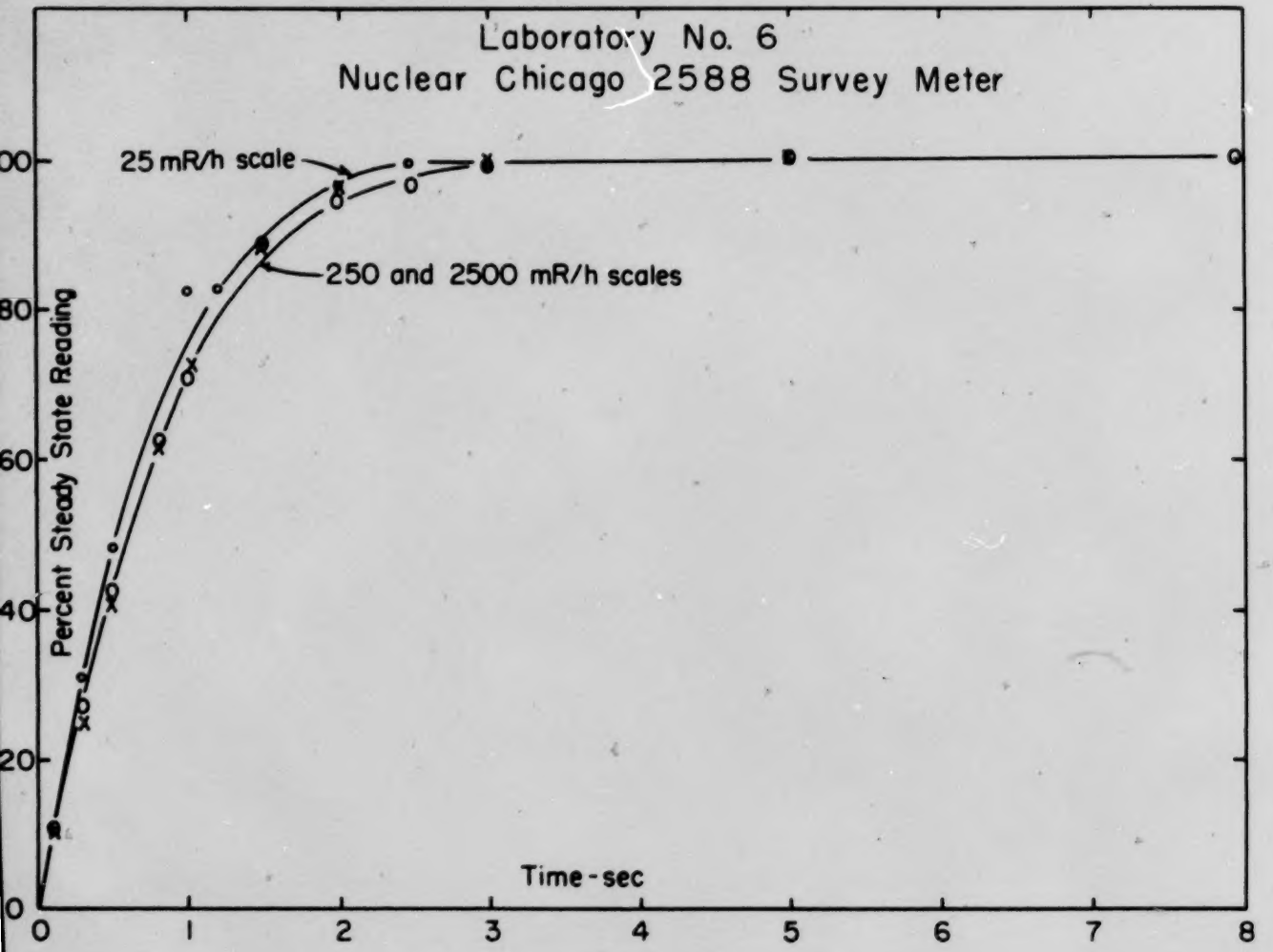
ANSWERS TO QUESTIONS

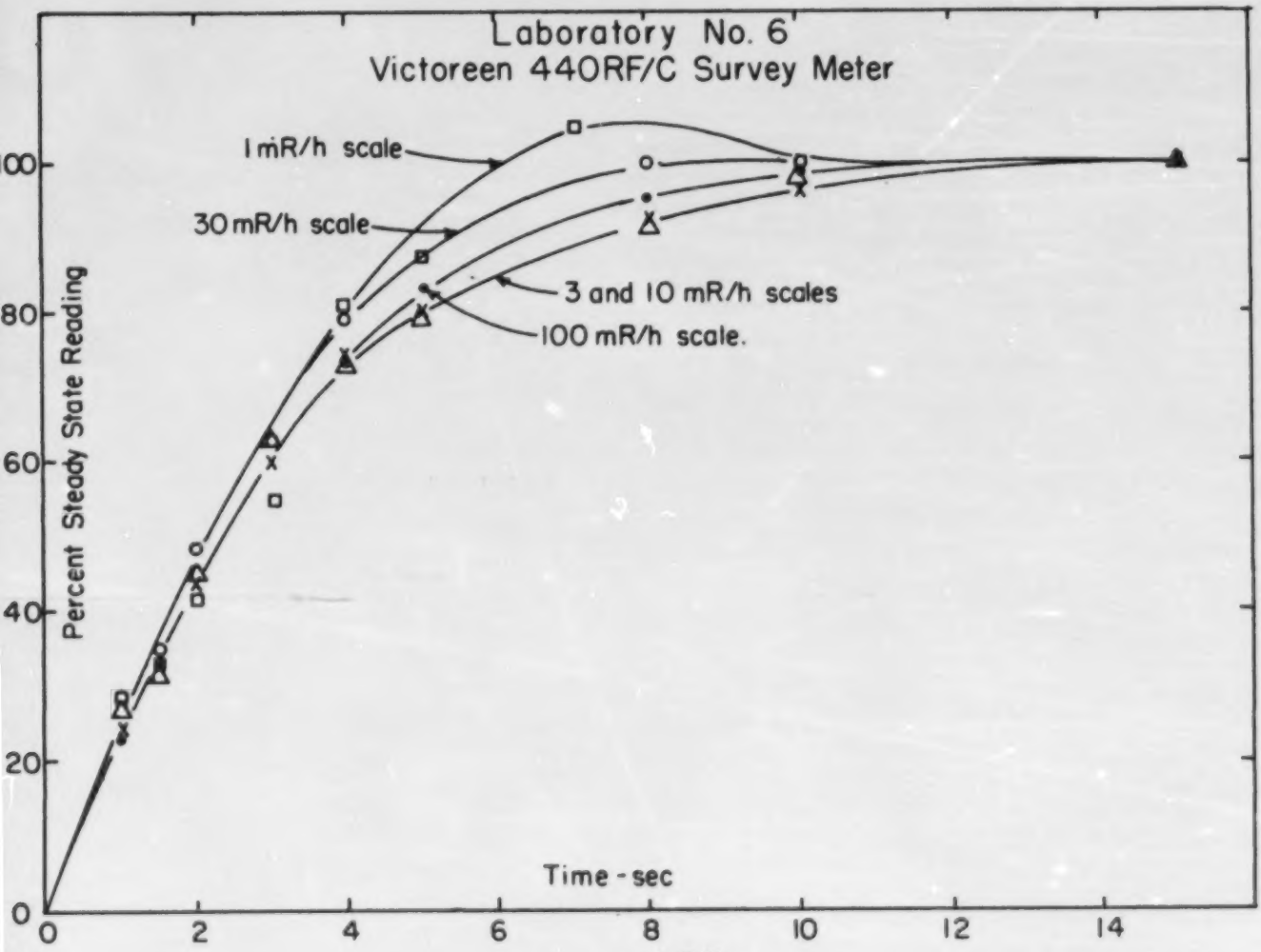
A. The duty cycle limitation of the source of radiation being surveyed may be such that radiation can only be produced for short periods of time. If the radiation "on" time is sufficiently short, the survey meter will not reach full response before the exposure is terminated. One must, therefore,know the response characteristics of the instrument in order to determine the actual value of the measured exposure rate.

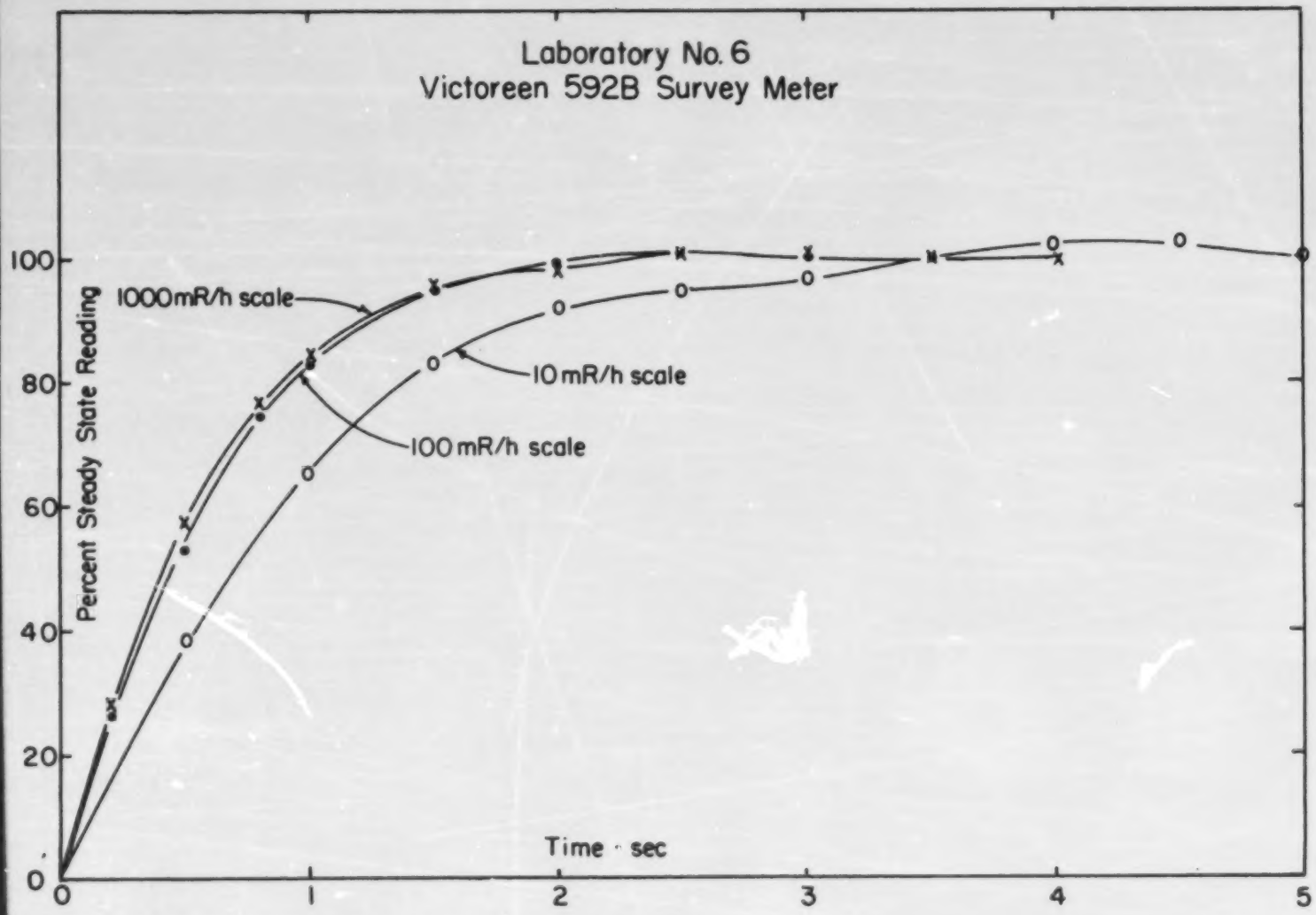
B. The time constant gives only the time required for the instrument to reach 63 percent of full response. One must have the entire response curve if accurate time response corrections are to be applied to the exposure rate indicated by the instrument.

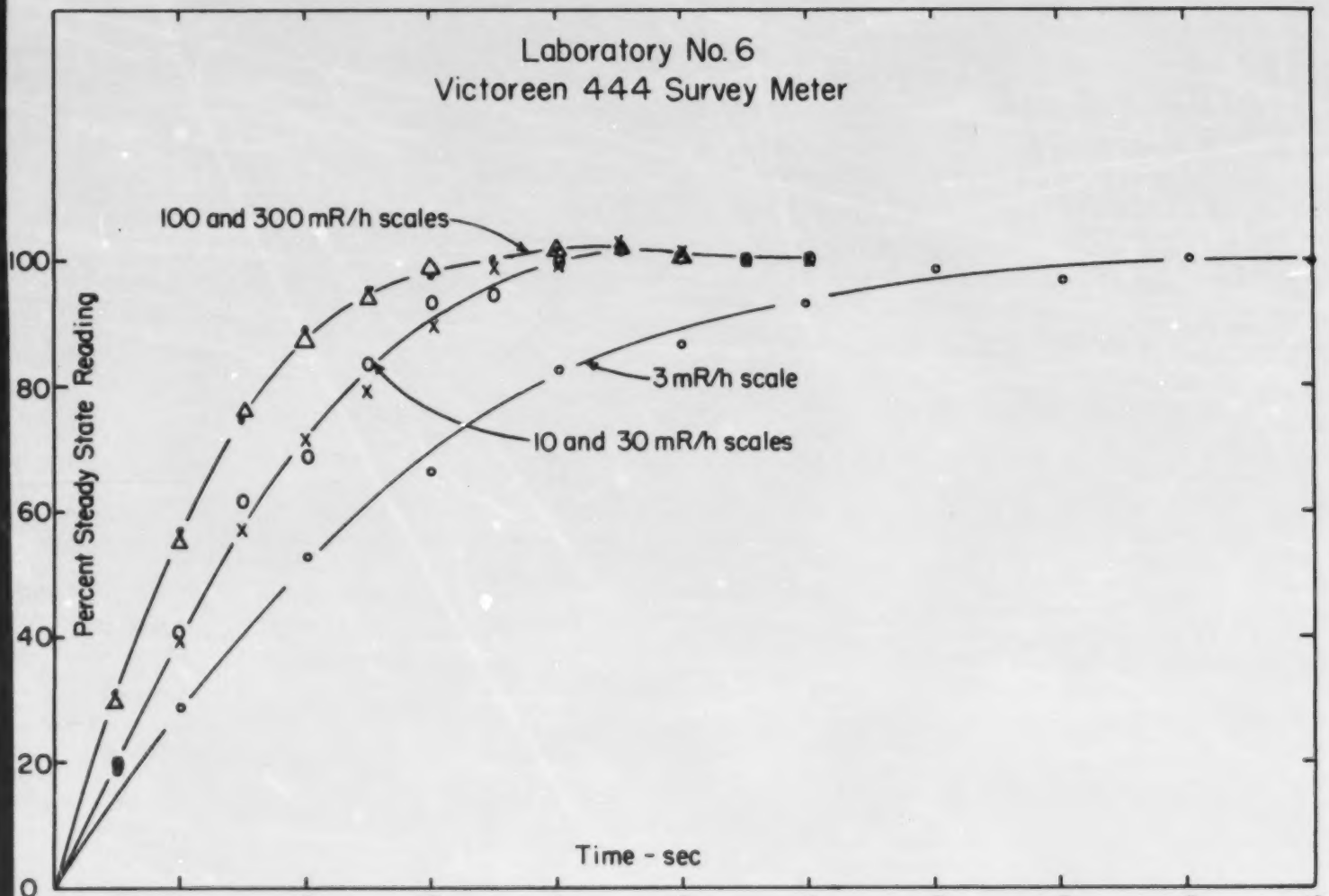
C. When changing from 100 mR/h to 3 mR/h, the value of the load resistor will increase by a factor of approximately 33-1/3. The voltage signals supplied by the ionization current circuit to the amplifier portion of the survey meter are a function of the ionization current and load resistor ($E = IR$). For the same output meter deflection, therefore, the resistance must increase as current decreases.

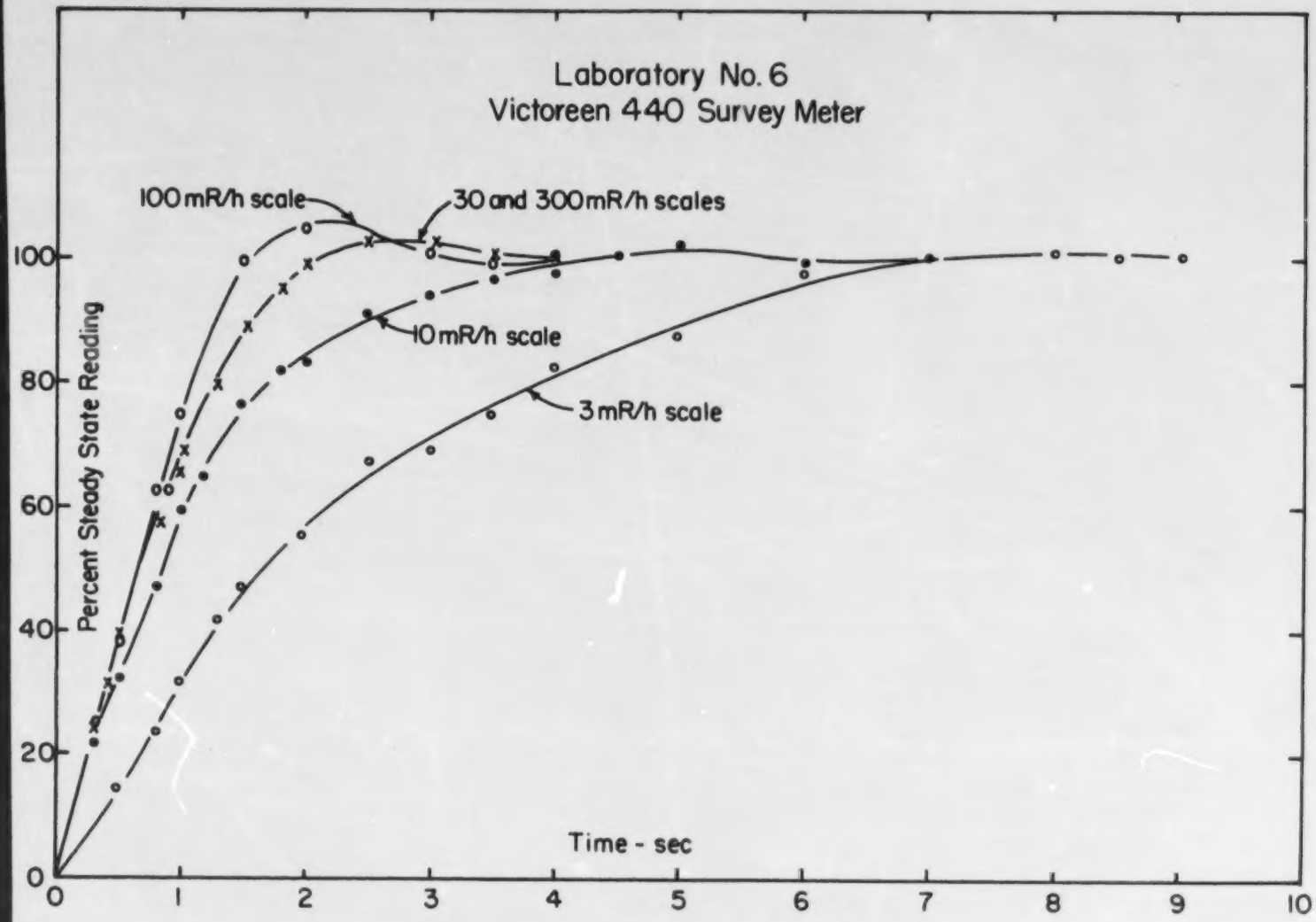

Laboratory No. 6
Victoreen Thyac GM Counter
Percent Steady State Reading
Fast
Medium
Slow
Time - sec
0
20
40
60
80
100
0
2
4
6
8
10
12
14
16

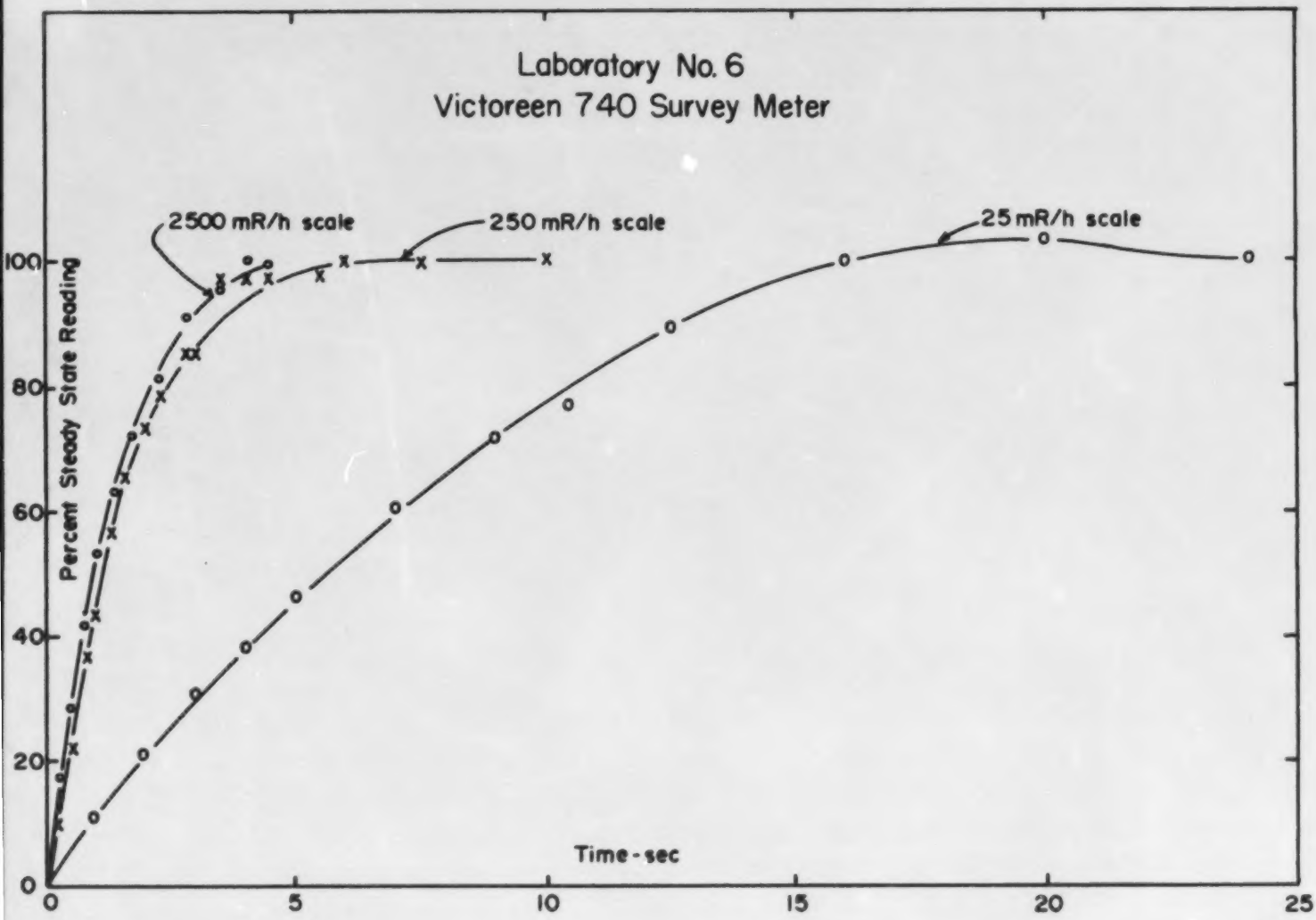

Laboratory No. 6
Nuclear Chicago 2588 Survey Meter
25 mR/h scale
250 and 2500 mR/h scales
Percent Steady State Reading
Time - sec
0
20
40
60
80
00
0
1
2
3
4
5
6
7
8


Laboratory No. 6
Victoreen 440RF/C Survey Meter
1 mR/h scale
30 mR/h scale
3 and 10 mR/h scales
100 mR/h scale.
Percent Steady State Reading
Time - sec
0
20
40
60
80
100
0
2
4
6
8
10
12
14


Laboratory No. 6
Victoreen 592B Survey Meter
Percent Steady State Reading
1000mR/h scale
10 mR/h scale
100 mR/h scale
Time - sec
0
20
40
60
80
100
0
1
2
3
4
5


Laboratory No. 6
Victoreen 444 Survey Meter
100 and 300 mR/h scales
3 mR/h scale
10 and 30 mR/h scales
Percent Steady State Reading
Time - sec
0
20
40
60
80
100
0
1
2
3
4
5
6
7
8
9
10


Laboratory No. 6
Victoreen 440 Survey Meter
100 mR/h scale
30 and 300 mR/h scales
10 mR/h scale
3 mR/h scale
Percent Steady State Reading
Time - sec
0
20
40
60
80
100
0
1
2
3
4
5
6
7
8
9
10


Laboratory No. 6
Victoreen 740 Survey Meter
2500 mR/h scale
250 mR/h scale
25 mR/h scale
Percent Steady State Reading
Time - sec
0
20
40
60
80
100
0
5
10
15
20
25

LABORATORY NO. 7

TITLE: Measurement of X-Ray Exposure with Personal Monitoring Film

PURPOSE: To study the techniques used to measure x-ray exposure with personal monitoring film

TIME: Two sessions of 2 hours each

MATERIALS FOR EACH STUDENT GROUP:

One Teaching X-Ray Unit
One Kodak model 4L dental processing hanger
Fourteen Kodak personal monitoring films -- Type 2
One Victoreen model 687 C-Minometer II
Two Victoreen model N3A 0-200 mR pocket chambers
One MacBeth model TD-102 densitometer
One film processing station
One lead sheet 10 x 15 x 0.08 cm (4 x 6 x 1/32 in.)
One sheet linear graph paper, K & E 46-0703 or equivalent
One ships curve, K & E 1685-48 or equivalent

REFERENCES:

Attix, Roesch, Tochilin
Radiation Dosimetry

Hine and Brownell
Radiation Dosimetry

NBS Handbook 57

LABORATORY NO. 7

7. MEASUREMENT OF X-RAY EXPOSURE WITH FILM

I. INTRODUCTION

To study the techniques used to measure x-ray exposure with personal monitoring film.

II. EQUIPMENT

A. Teaching X-Ray Unit

B. Nine personal monitoring film packets

C. Densitometer

D. One film hanger

E. Two 0-200 mR pocket chambers and charger-reader

F. One film processing station

G. One lead sheet

III. PROCEDURE

A. Number the films in the upper-hand corner from one to nine

B. Make the following exposures with the film packets placed on the center of the lead sheet with a pocket chamber on either side of the film to measure the exposure. Record the average of the two pocket chamber readings.

1. X-Ray machine settings

   60 kVp
   1.0 mA
   3 mm Al added filtration

2. Film exposures

Film No.	Approximate mR
1	15
2	30
3	45
4	60
5	75
6	90
7	110
8	130
9	Will be used as control. It is to be kept with the other films and not exposed to direct x ray

C. Develop the nine films plus five others to be obtained from the instructor. The additional five films have been exposed to radiation and the student will attempt to determine the exposures.

D. Film processing

1. Develop for 5 minutes at 20° C (68° F)
2. Rinse for 30 seconds
3. Fix for 10 minutes
4. Wash for 30 minutes
5. Dry

E. Read and record the film densities

F. Calculate net densities by subtracting the control film density from each of the other film densities

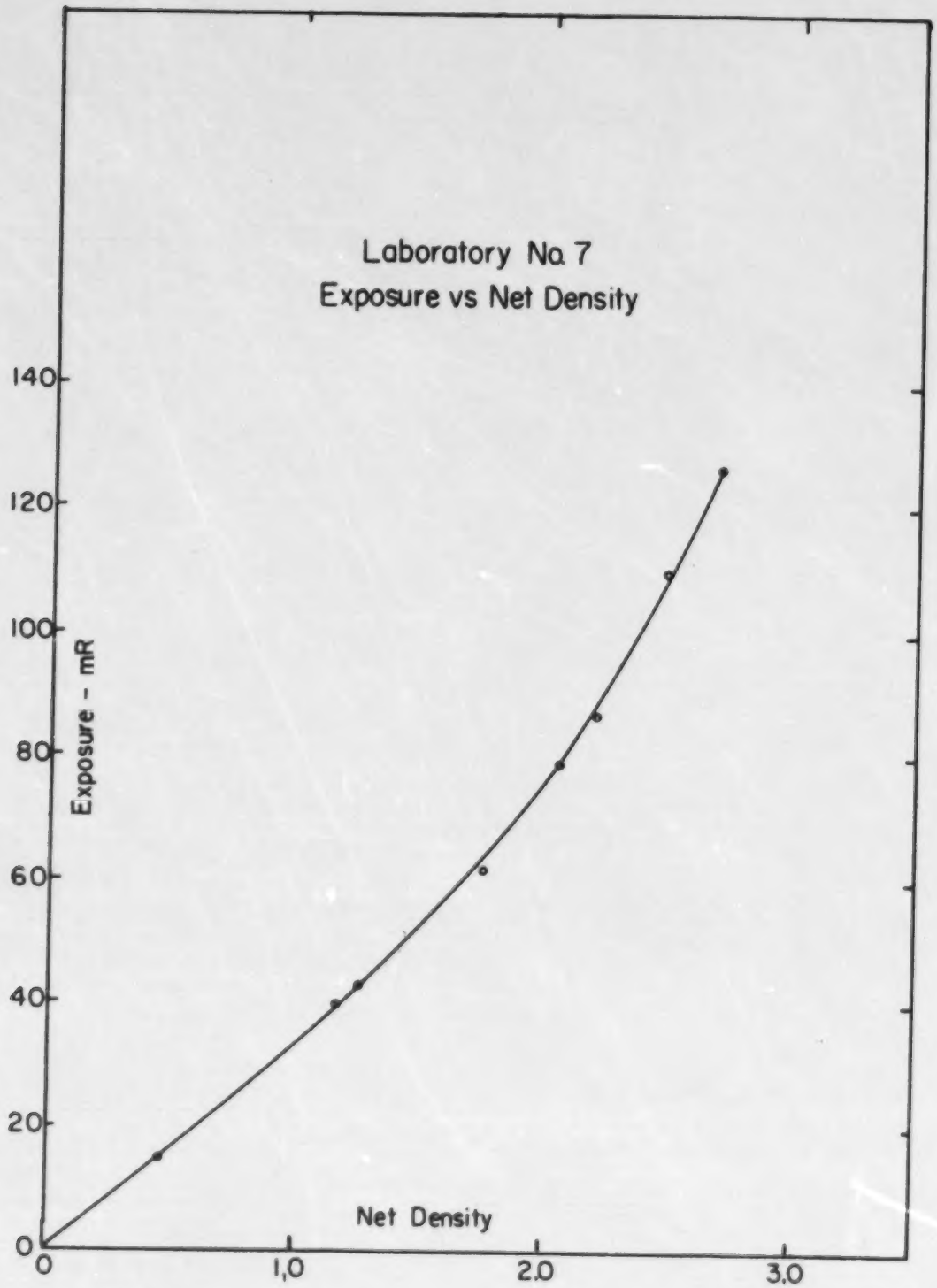
G. Plot net density versus exposure on linear graph paper

H. Determine the exposure of the unknowns from the calibration graph.

LABORATORY NO. 7

TYPICAL DATA

Film no.	kVp	Added mm Al	Exposure-mR	Density Gross	Density Net	Estimated Exposure-mR
1	60	3mmAl	15	0.76	0.45	--
2	60	3mmAl	40	1.47	1.16	--
3	60	3mmAl	43	1.57	1.26	--
4	60	3mmAl	62	2.06	1.75	--
5	60	3mmAl	79	2.36	2.05	--
6	60	3mmAl	87	2.51	2.20	--
7	60	3mmAl	110	2.79	2.48	--
8	60	3mmAl	127	3.00	2.69	--
9	60	3mmAl	0	0.31	0	--
Unknowns						
10	60	3mmAl	12	0.68	0.37	12
11	60	3mmAl	99	2.74	2.43	105
12	50	0	105	2.68	2.37	100
13	100	3mmAl	107	2.87	2.56	115
14	radium	gamma	215	0.91	0.60	20


Laboratory No. 7
Exposure vs Net Density
140
120
100
80
60
40
20
0
Exposure - mR
0
1.0
2.0
3.0
Net Density

LABORATORY NO. 8

TITLE: X-Ray Protection Survey

PURPOSE: To allow the student to perform radiation protection surveys of a typical diagnostic and a typical therapeutic x-ray installation

TIME: 3 hours

MATERIALS FOR EACH STUDENT GROUP:

One General Electric DXR-750
One General Electric Maxitron 300
One General Electric Maximar 100
One General Electric Mobile CMX-110
One water phantom (25 x 25 x 25 cm)
One Victoreen Model 440 survey meter
One Victoreen Model 444 survey meter
One Victoreen Model 592B survey meter
One Victoreen Model 490 survey meter
One Victoreen Model 740B survey meter
One Victoreen Radector II survey meter

REFERENCES: NCRP Report No. 33

NCRP Report No. 34

Oregon State Regulations for the Control of Radiation

LABORATORY NO. 8

8. X-RAY PROTECTION SURVEY

I. INTRODUCTION

The purpose of this laboratory exercise is to have the student select the instrumentation necessary and to perform radiation protection surveys of a diagnostic and a therapeutic x-ray installation.

II. EQUIPMENT AND INSTALLATIONS

A. General Electric DXR-750

B. General Electric Maximar 100

C. General Electric Mobile CMX-110

D. General Electric Maxitron 300

E. Water phantom

F. Selected survey instruments

III. PROCEDURE

A. Survey of a therapeutic x-ray installation

1. Limit the survey to adjacent room (personnel) protection
2. Select the instrumentation necessary
3. Determine what exposure measurements must be made
4. Make a sketch of the installation
5. Record the shielding, workload, use factor, etc., data
6. Obtain and record the necessary exposure data

B. Survey of a diagnostic radiographic installation

1. Follow the procedure in part III.A.

IV. PREPARATION OF REPORT

A. Prepare a report as if you are a consultant called in by the laboratory director and charged with the task of surveying these installations. Include as part of your report the instrumentation used, the exposure conditions, the survey data, use and occupancy factors, and your conclusions and recommendations.

SECTION III. EXAMINATIONS

GS-462. X-RAY MEASUREMENTS

Name _____

GS-462 X-Ray Measurements
Test No. 1

Part I. Multiple choice. Circle the letter or letters preceding the answer or answers which correctly complete the statement. Grade value 3 points each.

1. The half-value layer of a 30 keV photon beam is approximately 2.4 mm of aluminum. The thickness of aluminum that will reduce the beam intensity to 12½ percent of its original intensity is:

   a. 2.4 mm.
   b. 4.8 mm.
   (c) 7.2 mm.
   d. 9.6 mm.
   e. 12.0 mm.

2. The predominant mechanism for attenuation of a 500 keV beam of photons in tissue is:

   a. the photoelectric effect.
   (b) the Compton effect.
   c. pair production.
   d. triplet production.
   e. coherent scattering.

3. The rad:

   a. is the special unit of dose equivalent.
   b. is defined only in air.
   (c) is equivalent to 10^{-2} J kg^{-1}.
   d. relates exposure to absorbed dose.
   e. is used only in radiation protection.

4. The roentgen:

   (a) is the special unit of exposure.
   (b) is defined only in air.
   (c) is equivalent to 2.58 x 10^{-4} C kg^{-1}.
   (d) applies only to x and/or gamma radiation.
   e. is used only in radiobiology.

5. The field distribution parallel to the x-ray tube axis of the x-ray beam from a reflection target x-ray tube is influenced by:

   (a) the x-ray tube target angle.
   (b) the kilovoltage.
   c. the x-ray tube current.
   (d) the thickness of the added filtration.
   (e) the "heel effect."

6. In a gas-filled ionization chamber instrument used to measure exposure rate, the ionization current is:

   (a) directly proportional to the incident x-ray intensity.
   b. inversely proportional to the incident x-ray intensity.
   c. independent of x-ray intensity.
   d. read using a 0-100 ampere d.c. meter.
   e. independent of the volume of gas in the chamber.

7. In attenuation of a photon beam in matter by the photoelectric effect:

   a. all of the photon's energy is transferred to kinetic energy of the photoelectron.
   b. only "free" or "loosely bound" electrons are involved.
   c. the threshold energy is 1.02 keV.
   (d) the photons give up all of their energy in a single interaction.
   e. none of the above.

8. Use of the half-value layer was initially proposed by:

   a. J. Victoreen.
   b. W. Coolidge.
   (c) T. Christen.
   d. A. Lucas.
   e. W. Roentgen.

9. The homogeneity coefficient:

   (a) is the ratio of the first half-value layer to the second half-value layer.
   b. is the ratio of the second half-value layer to the first half-value layer.
   c. is never less than 1.
   d. decreases as mA decreases.
   e. is independent of kilovoltage.

10. When changing from a low (25 mR/h) full-scale range to a high (2500 mR/h) full-scale range on a typical ionization chamber survey meter:

    a. the chamber load resistor will increase by a factor of 100.
    (b) the chamber load resistor will decrease by a factor of 100.
    c. the chamber air volume will increase by a factor of 100.
    d. the chamber air volume will decrease by a factor of 100.
    e. there will be no change in either chamber load resistance or chamber volume.

Part II. True-false. Write T on the line preceding the statement if all parts of the statement are true. Write F if any part of the statement is false.

Grade value is 2 points each.

(F) 1. All other factors constant, the broad beam half-value layer will decrease as source-chamber distance decreases.

(T) 2. The "unique" half-value layer for a given x-ray beam is independent of measuring geometry.

(F) 3. A 100 kVp x-ray beam will always have a homogeneity coefficient greater than a 50 kVp x-ray beam.

(T) 4. For radiation protection purposes 1 R = 1 rad = 1 rem.

(T) 5. All other factors constant, the "heel effect" would be more pronounced with an x-ray tube target angle of 11° than a target angle of 45°.

Part III. Discussion/Problems.

Grade value shown in parenthesis for each question.

1. Define, in the space provided, the following:

(4) a. Ionizing radiation

Ans. A beam of directly or indirectly ionizing particles or a mixture of both.

(4) b. Exposure

Ans. Charge per unit mass of air due to photon interactions.
$x = dQ/dm$.
Special unit, roentgen.
$1\ R = 2.58 \times 10^{-4}\ C/kg$ air

(4) c. Effective energy

Ans. Energy, keV, of a monoenergetic beam with the same 1 HVL as the heterogeneous beam.

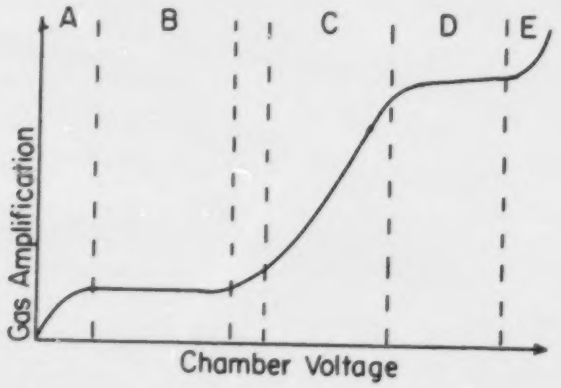
(4) d. Absorbed dose

Ans. Energy absorbed per unit mass of material.
$D = dE/dm$.
Special unit, rad
$1\ rad = 10^{-2}\ J/kg$

(4) e. R-meter sensitivity

Ans. Change in voltage per roentgen of exposure.
$S = dV/dR$

(20) 2. Draw the gas amplification versus chamber voltage curve for a typical ionization chamber. Label and briefly define each of the 5 regions of the curve.



A. Recombination region. V so low ions recombine.
B. Ionization chamber region. Essentially all ions produced are collected.

C. Proportional region. Amplification typically 10^3 - 10^4. Ions collected proportional to number initially produced.
D. G.M. region. Amplification 10^8. Counts individual events.
E. Continues discharge region. Arc.

3. Copper transmission data at 300 kVp with two field sizes at the added absorbers were determined to be as follows:

Percent Transmission	5 cm dia. Field Added Absorber - mm Cu	10 cm dia. Field Added Absorber - mm Cu
100	0	0
50	2.05	2.10
25	5.32	5.46

(5) a. What are the 1 HVL and 2 HVL for each field size?

Ans.

5 cm dia. field	10 cm dia. field
1 HVL = 2.05 mm Cu	1 HVL = 2.10 mm Cu
2 HVL = 3.27 mm Cu	2 HVL = 3.36 mm Cu

(5) b. What are the unique 1 HVL and 2 HVL?

Ans. $1\ HVL_o = 2.05 - (2.10 - 2.05) = 2.00$ mm Cu
$2\ HVL_o = 3.27 - (3.36 - 3.27) = 3.18$ mm Cu

(5) c. What is the unique homogeneity coefficient?

Ans. $H_o = 2.00/3.18 = 0.629$

(5) d. What is the effective energy of the beam in keV (density of copper 8.89 g cm^{-3})?

Ans. $M/P = 0.693/(0.2)\ (8.89) = 0.39\ cm^2/g$
From attached curve 109 keV

Name _____

GS-462 X-Ray Measurements
Final Examination
Total Grade Value 175 Points

Part I. MULTIPLE CHOICE. Circle the letter or letters preceding the answer or answers which correctly completes the statement or answers the question.

Grade value 4 points each.

1. The density of a radiograph is 2.0. This corresponds to a light transmission through the radiograph of:

   a. 10^2.
   b. 2^{10}.
   (c) 10^{-2}.
   d. 2-10.
   e. 2.0.

2. The energy of photons scattered from tissue by the Compton effect at 180° to the incident central beam is:

   a. never less than the incident photon energy.
   (b) never greater than 255 keV.
   c. never greater than 511 keV.
   d. directly proportional to x-ray tube current.
   e. none of the above

3. Which of the following are directly ionizing particles?

   a. Photons.
   (b) Protons.
   c. Neutrons.
   (d) Electrons.
   (e) Positrons.

4. The primary standard for the measurement of exposure:

   (a) is the standard (free) air chamber.
   b. is the Victoreen Condenser R-Meter.
   (c) has a defined air volume surrounded by air.
   d. has a wall of air-equivalent plastic.
   e. has an aluminum center electrode.

5. A survey meter is exposed to an x-ray beam of constant exposure rate for a period of time equal to the time constant of the instrument and indicates 1 mR/h. Approximately what would be the meter reading if exposed to the x-ray beam for a period of time 10 times the time constant?

   a. 1 mR/h.
   (b) 1.6 mR/h.
   c. 3 mR/h.
   d. 3.6 mR/h.
   e. 10 mR/h.

6. Which of the following is best suited for exposure measurements to determine the total monthly exposure of an individual?

a. Condenser R-meter.
b. Proportional counter.
c. GM counter.
(d) Personal monitoring film.
e. Fluorescent screen.

7. The half-value layer of a monoenergetic narrow beam of x rays is 0.5 mm of lead. The thickness of lead that will reduce the exposure rate to 10 percent of its initial value is approximately:

a. 1.0 mm.
(b) 1.6 mm.
c. 2.8 mm.
d. 4.1 mm.
e. 5.0 mm.

$T = e^{-0.693N} = 0.1$
$e^{-2.30} = 0.1$
$.693N = 2.3$
$N = 3.32$
$(.5)\ (3.32) = 1.66$ mm

8. Thermoluminescent materials in common use include:

a. $CaWO_4$.
(b) LiF.
(c) CaF_2.
d. AgBr.
e. ZnCdS.

9. A DC amplifier-type survey meter:

(a) has an electrometer tube amplifier.
b. is inherently drift-free.
c. has a vibrating reed to convert the a.c. ion current to d.c.
d. is more sensitive than all other types of survey meters.
e. has no zero adjust control.

10. In which of the following interactions of x rays with matter do the photons give up <u>all</u> of their initial energy in a single interaction?

(a) Photoelectric effect.
b. Compton effect.
c. Coherent (elastic) scatter.
(d) Pair production.
(e) Triplet production.

11. The x-ray field distribution on a plane parallel to the x-ray tube axis is influenced by the:

(a) x-ray tube target angle.
(b) x-ray tube kilovoltage.
(c) thickness of the added filtration.
d. x-ray tube current.
(e) inverse-square law.

Part II. MATCHING. In the blank space provided at the beginning of each of the following statements, write the letter or letters corresponding to the correct term taken from the list that follows the statements.

Grade value 3 points each.

1. (j) unit of exposure
2. (h) unit of absorbed dose
3. (i) unit of dose equivalent
4. (q) radiographic density
5. (g) time constant
6. (d) predominates at low energies
7. (o) long-term MPD for occupationally exposed personnel
8. (n) homogeneity coefficient
9. (b) absorbed dose in air
10. (p) equivalent of 1 R
11. (s) diagnostic-type protective tube housing
12. (f) negative charges

a. photons
b. 0.87 X
c. Compton effect
d. photoelectric effect
e. pair production
f. electrons
g. RC
h. rad
i. rem
j. roentgen
k. 0.5 rem
l. x rays
m. log T
n. 1 HVL/2 HVL
o. 5(N-18) rem
p. 2.58×10^{-4} C/kg
q. log 1/T
r. 100 esu/g
s. 100 mR in 1 h at 1 m
t. 1 R in 1 h at 1 m

PART III. PROBLEMS/DISCUSSION. Read each question carefully. Show all work. Grade value shown in parenthesis for each question.

(5) 1. Answer any 3 of the 4 parts (a, b, c, or d) of this question.

a. An air equivalent ionization chamber is exposed to a 100 keV photon beam and the ionization current determined to be 5.85 x 10-10 ampere. If the chamber response at this energy is 1.45×10^{10} R/ampere/minute, what is the exposure rate in R/minute?

Ans: $X/T = (5.85 \times 10^{-10}\ A)\ (1.45 \times 10^{10}\ R/A\text{-min}) = 8.48\ R/min$

(5) b. An air equivalent ionization chamber is placed in muscle tissue and exposed to 300 keV photons. The chamber volume is 0.1 cm^3, the charge collected is 100 esu and the factor "f" is 0.958. What is the absorbed dose in the muscle at the location of the chamber?

Ans: $D = fX = (0.958)\ (100/0.1) = 958$ rad

(5) c. At 100 keV the mass energy transfer coefficient for air is 0.0234 cm^2/g and for compact bone 0.0387 cm^2/g. What is the absorbed dose in bone if the measured exposure is 50 R?

Ans. $D = 0.87X\ \frac{\mu k/\rho\ (mat'l)}{\mu k/\rho\ (air)} = (0.87)\ (50)\ (\frac{0.0387}{0.0234})$

$= 71.9$ rads

(5) d. An R-meter chamber exposed to a 50 keV photon beam indicates 15 R for a 30 second exposure. If the temperature-correction factor is 1.045 and the chamber response (indicated/actual exposure) is 1.02 at 50 keV, what is the exposure rate in R/minute?

Ans. $X/t = (15)\ (\frac{60}{30})\ \ (\frac{1.045}{1.02}) = 30.7$ R/min

(10) 2. List 5 factors that influence the thickness of a protective barrier required to reduce the exposure in an area to a given level.

Ans. 1. Quality (energy, kVp) of radiation.
2. Quantity (mA-min, R) of radiation produced in a given time.
3. Distance (ISL) of point of interest from radiation source.
4. Degree and nature of occupancy at point of interest.
5. Type (controlled, noncontrolled) of area.
6. Barrier material used.

3. Define, <u>in the space provided</u>, 5 of the 7 following terms.

(5) a. Scattered radiation

Ans. Radiation that, during passage through matter, has been deviated in direction with or without a change in energy.

(5) b. Therapeutic-type protective tube housing (less than 500 kV)

Ans. An x-ray tube housing so constructed that the leakage radiation at a distance of 1 m from the source does not exceed 1 R in 1 hour when the tube is operated at its maximum rated continuous tube current for the maximum rated tube potential.

(5) c. Controlled area

Ans. Defined area in which the exposure of persons to radiation is under the supervision of a Radiation Protection Supervisor. This implies control of access, occupancy and working conditions.

(5) d. Stray radiation

Ans. The sum of leakage and scattered radiation.

(5) e. Half-value layer

Ans. The thickness of a specified substance which, when introduced into the path of a given beam of radiation, reduces the exposure rate by one-half.

(5) f. Electronic equilibrium

Ans. Number of electrons entering volume element of air = number leaving volume element.

(5) g. R-meter sensitivity

Ans. Voltage change (decrease) per roentgen of exposure

$$S = \frac{dV}{dR}$$

4. An x-ray machine is operating at 150 kVp, 100 mA. The instantaneous exposure rate measured in the x-ray control area is 0.5 R/hour. If the workload for this installation is 100 mA-min/week:

(10) a. What is the exposure in the x-ray control area in mR in 1 week?

Ans. $X/t = (0.5\ R/h)\ \frac{(100\ mA\text{-}min/wk)}{(100\ mA)\ (60\ min/h)} = 0.0083\ R/wk$

(5) b. Is this exposure above or below the "design" maximum weekly exposure for a controlled area? Explain briefly.

Ans. Below. The design maximum weekly exposure for a controlled area is 0.1 R/week.

5. Transmission through copper at 300 kVp with 2 field sizes at the added absorbers were determined to be as follows:

Percent Transmission	5 cm dia. field	10 cm dia. field
	Added Absorber-mm Cu	
100	0	0
50	3.17	3.72
25	7.02	7.98

(10) a. What are the first and second half-value layers for each field diameter?

Ans. 1 HVL_5 = 3.17 mm Cu 1 HVL_{10} = 3.72 mm Cu

2 HVL_5 = 7.02 - 3.17 = 3.85 mm Cu

2 HVL_{10} = 7.98 - 3.72 = 4.26 mm Cu

(10) b. What are the unique first and second half-value layers?

Ans. Unique 1 HVL = 3.17 - (3.72 - 3.17) = 2.62 mm Cu
Unique 2 HVL = 3.85 - (4.26 - 3.85) = 3.44 mm Cu

(5) c. What is the unique homogeneity coefficient?

Ans. $H_o = \frac{2.62}{3.44} = 0.76$

(5) d. What is the mass attenuation coefficient corresponding to the unique first half-value layer (density of copper 8.9 g/cm^3)?

Ans. $\mu/\rho = \frac{0.693}{(0.262)\ (8.9)} = 0.297\ cm^2/g$

APPENDICES

A. - EQUIPMENT LIST

B. - BIBLIOGRAPHY

APPENDIX A. EQUIPMENT LIST

The following is a list of equipment needed for each student laboratory group. Major equipment items would, of course, be used by all laboratory groups. Equipment not generally commercially available and fabricated in the X-Ray Science and Engineering Laboratory and University shops is detailed at the end of this appendix.

Number Required	Item
1	Victoreen model 440 survey meter
1	Victoreen model 444 survey meter
1	Victoreen model 740B survey meter
1	Victoreen model 592B survey meter
1	Victoreen model 570 condenser R-meter
1	Victoreen model 70-5, 25 R chamber
1	Victoreen model 687C Minometer II
2	Victoreen model N3A, 0-200 mR pocket chambers
1	Nuclear Associates model PTW, 20 mR alarm
1	Nuclear Chicago model 2588 survey meter
1	Bendix model 1200MR, 0-200 mR low energy pocket dosimeter
1	Bendix model NS, 0-200 mR pocket dosimeter
1	Bendix model 906-1 dosimeter charger
2	Victoreen model 555 Radocon II
2	Victoreen model 555-0.1 MA probe
1	Victoreen model 555-0.1 DAS probe
1	Victoreen model 555-1 DAS probe
2	Ring stands with clamps
1	General Electric Maximar 100 x-ray machine
1	Mercury barometer
1	Mercury thermometer
1	MacBeth model TD-102 densitometer
14	Kodak Personal Monitoring Films, Type 2
1	Kodak model 4L dental film processing hanger
1	Nuclear Data Corp. model ND-A 512 channel analyzer
1	Harshaw 3.8 x 1.6 cm NaI (Tl) crystal and photo-multiplier tube assembly with 0.0125 cm beryllium window and 0.5 mm diameter collimeter
1	3 M human chest phantom
1	7.5 cm Heath Co. d.c. oscilloscope
1	Solid state (solar cell) x-ray detector with pre-amplifier.
1	Teaching X-Ray Unit, described in USPHS Publication No. 1859

Number Required	Item
1	General Electric Co. 90 kVp mobile x-ray unit. This unit consists of a G.E. 90 kVp dental tube head and control both mounted on a mobile tube stand. The tube head was modified in that the 1.5 mm Al filter built into the head was removed so that the total inherent filtration was equivalent to approximately 1 mm Al and an external filter box and beam defining cone adapter was attached to the threaded dental cone adapter. The filter/adapter assembly accommodates the Maximar 100 filters and cones. Control modifications included the following: a. The stabilized 10 and 15 mA tube current selection was replaced with a continuously variable 0.5-6 mA tube current control. A 6 mA tube current meter was included in the control panel (see c below). b. The kVp meter was recalibrated to indicate kVp at 1, 3, and 5 mA tube current. c. The electronic timer and its control switch were removed. The mA meter (a above) was installed in the control at the location of the timer control switch.
1	X-ray film processing station. This is a self-contained film developing station including a dental processing tank (containing one gallon tanks for developer and fixer as well as the wash tank), counter space, and shelf space for film cassettes and film hangers. The tanks will accommodate film up to 20 x 25 cm. Drawings of the station are shown in figures 462-54 and 462-55.

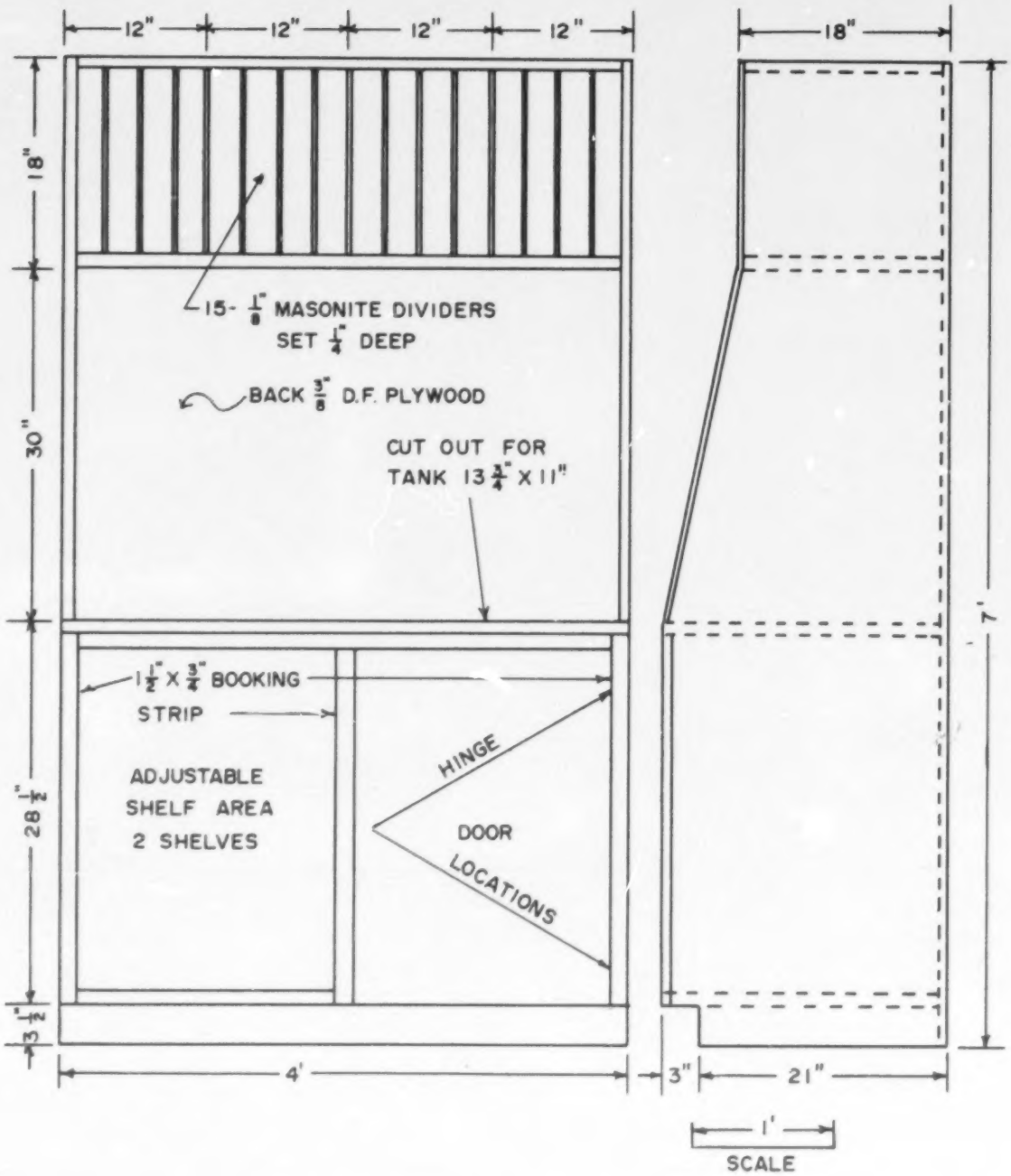


Figure 462-54. Film processing station.

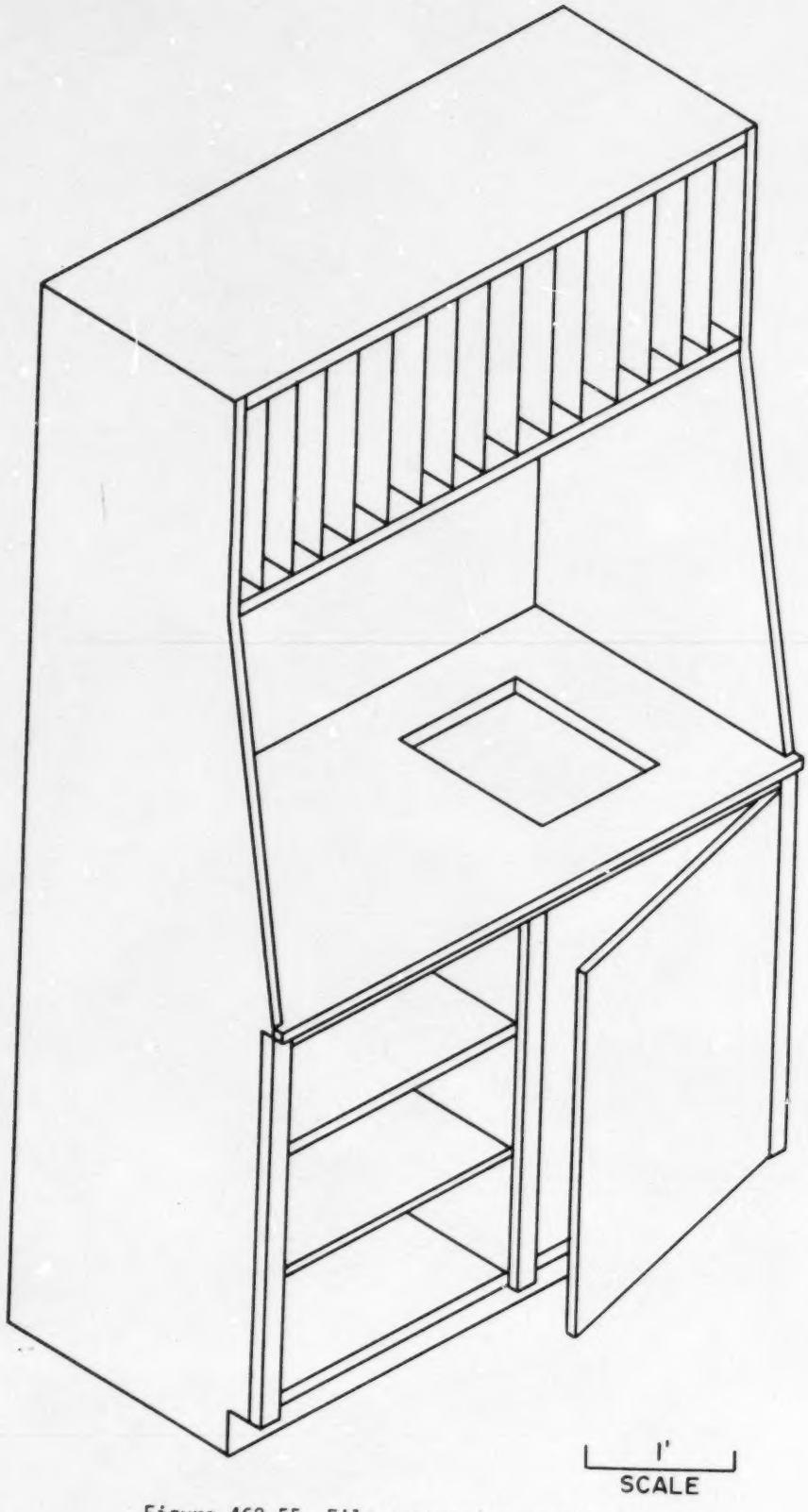


Figure 462-55. Film processing station.

APPENDIX B. BIBLIOGRAPHY

Atlee, Z. J. and E. D. Trout. "A study of reontgen-ray distribution at 60 - 140 kVp." Radiology 40:4 (1943).

Atrix, F.A., W. C. Roesch, and E. Tochilin, Radiation Dosimetry, Volume II (New York: Academic Press, 1972).

Bacq, Z. and P. Alexander, Fundamentals of Radiobiology (New York: Pergamon Press, 1963).

Cameron, J. R., N. Suntharalingam, and G. N. Kenney, Thermoluminescent Dosimetry (Wisconsin: University of Wisconsin Press, 1968).

Chorzempa, Sister Mary Andre, Ionizing Radiation and its Chemical Effect: A Historical Study of Chemical Dosimetry (1902-1962) (Oregon: Oregon State University doctoral thesis (Ph.D.) 1971).

Commission of the European Communities. International Symposium. Radioecology Applied to the Protection of Man and His Environment, Volumes I & II (1971).

Etter, L. E., The Science of Ionizing Radiation (Illinois: Charles C. Thomas, Publisher, 1965).

Evans, R. D., The Atomic Nucleus (New York: McGraw-Hill Book Company, 1955).

Fowler, J. F. "Solid state dosimetry." Phys Med Biol 8:1-32 (1963).

Glasstone, S. (Editor), The Effects of Nuclear Weapons, U. S. Atomic Energy Commission. Superintendent of Documents, U.S. Government Printing Office,Wash., D.C. 20402.

Hendee, W. R., Medical Radiation Physics (Illinois: Year Book Medical Publishers, Inc., 1970).

Hine, G. J. and G. L. Brownell, Radiation Dosimetry (New York:Academic Press, Inc., 1956).

Howl, Barbara, M.S.R.T., S.R.R., Simplified Physics for Radiology Students (Illinois: Charles C. Thomas, Publisher, 1971).

International Commisston on Radiation Units and Measurements. Report No.19, Radiation Quantities and Units (Washington, D.C.: International Commission on Radiation Units and Measurements Publications, 1971).

International Commission on Radiation Units and Measurements. Report No. 11, Radiation Quantities and Units (Washington, D.C.: International Commission on Radiation Units and Measurements Publications, 1968).

International Commission on Radiological Protection (New York:Pergamon Press).

Publication 3. Protection Against X-Rays up to Energies of 3 MeV and Beta- and Gamma-rays from Sealed Sources, 1960.

Publication 15. Protection Against Ionizing Radiation from External Sources, 1969.

Publication 16. Protection of the Patient in X-Ray Diagnosis, 1969.

Johns, H. E. and J. R. Cunningham, The Physics of Radiology (Illinois: Charles C. Thomas, Publisher, 1969).

Meredith, W. J. and J. B. Massey, Fundamental Physics of Radiology (Maryland: Williams and Wilkins, Co., Publisher, 1968).

National Bureau of Standards Handbooks, U.S. Department of Commerce. Superintendent of Documents, U.S. Government Printing Office, Washington, D. C. 20402.

Handbook 57, Photographic Dosimetry of X- and Gamma-rays, 1954.

Handbook 64, Design of Free-Air Ionization Chambers, 1957.

Handbook 85, Physical Aspects of Irradiation (ICRU Report 10b), 1964.

Handbook 87, Clinical Dosimetry (ICRU Report 10d), 1963.

Handbook 93, Safety Standards for Non-Medical X-Ray and Sealed Gamma-Ray Sources, 1964.

National Council on Radiation Protection and Measurements Reports (Washington, D.C.: National Council on Radiation Protection and Measurements Publications).

Report 33, Medical X-Ray and Gamma-Ray Protection for Energies up to 10 MeV: Structural Shielding Design and Evaluation, 1970.

Report No. 35, Dental X-Ray Protection, 1970.

Report No. 36, Radiation Protection in Veterinary Medicine, 1970.

Report No. 39, Basic Radiation Protection Criteria, 1971.

Oregon State Board of Health. Regulations for Control of Radiation for Use in the Healing Arts (Oregon: Oregon State Board of Health, 1969).

Overman, G. T. and H. M. Clarke, Radioisotope Techniques (New York: McGraw-Hill Book Company, 1060).

Randell, J. T. and M. H. F. Wilkins, Phosphorescence and Electron Traps, Proceedings of the Royal Society of London, Series A, 184:366-389 (London: 1945).

Schwartz, E. E. (Editor), The Biological Basis of Radiation Therapy (Pennsylvania: J. B. Lippincott, Company, 1966).

Snell, A. H., Nuclear Instruments and Their Uses, Volume 1 (New York: John Wiley and Sons, Inc., 1962).

Spiers, F. W. and G. W. Reed (Editors), Radiation Dosimetry (New York: Academic Press, 1964).

Stanton, L., Basic Medical Radiation Physics (New York: Appleton-Century-Crofts Publishers, 1969).

Taylor, Lauriston S., Radiation Protection Standards (Chemical Rubber Company Press, 1971).

Ter-Pogossian, The Physical Aspects of Diagnostic Radiology (New York: Harper and Row, Publishers, 1967).

Trout, E. D., J. P. Kelley, and A. C. Lucas. "Influence of cable length on dose rate and half-value layer in diagnostic x-ray procedures." Radiology 74:2 (1960).

Trout, E. D., J. P. Kelley, and A. C. Lucas. "Determination of half-value layer." Am J Roentgenol 84:4 (1960).

Trout, E. D., J. P. Kelley, and A. C. Lucas. "The second half-value layer and the homogeneity coefficient." Am J Roentgenol 87:3 (1962).

U.S. Department of Health, Education, and Welfare, Public Health Service. Radiological Health Handbook, Revised Edition January 1970. Superintendent of Documents, U. S. Government Printing Office, Washington, D.C. 20402. Stock No. 017-011-00043-0, Price, $5.25.

Whyte, G. N., Principle of Radiation Dosimetry (New York: John Wiley and Sons Inc., 1959).

U.S. GOVERNMENT PRINTING OFFICE: 1977 O-241-413/1346

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